Teleconnections in EBUS:
a focus on oceanic coastally trapped waves

A. Lazar,
A.C. Peter, M. Wade, L. Poli, B. Sané

LOCEAN, Sorbonne University, Paris, France
LPAO, Dakar University, Senegal

Mean Reynolds SST (°C), ORCA05-PISCES Chl contours (mg/m³)
Teleconnections in EBUS:
a focus on oceanic coastally trapped waves
Teleconnections in EBUS: a focus on oceanic coastally trapped waves

Geostrophy, Rossby waves and westward intensification

Some consequences of Rule 1: Rossby waves and western boundary currents

We consider a 1/2-layer ocean - to define the sign of $f$, we take it in the southern hemisphere - with the bottom layer at rest. Suppose there is a large region in which the layer depth $H$ is deeper than in surrounding regions, where both layers are at rest (i.e., $H$ is constant there). Figure 3.4 shows a map of $H$ for this situation. Appropriately scaled (by the factor $\Delta \rho / \rho_0$; see eqn (3.6) above) it is also a map of steric height, from which the flow at all depths in the upper layer can be deduced through eqn (3.4). It is seen that the feature represents a large anticyclonic eddy.

Fig. 3.4. Plan view of the eddy of Fig. 3.3. A and B are two points on the western side of the eddy at latitude $y_1$, on two isobars separated by an amount $\Delta h = \Delta \rho (H_1 - H_2) / \rho$ in steric height. C and D are two similar points at latitude $y_2 = y_1 + \Delta y$. By eqn (3.4), total southward flow is greater in magnitude between A and B than between C and D because $f$ is smaller in magnitude at A and B than at C and D; the thermocline deepens in ABCD. By the same argument, the thermocline shallows in A'B'C'D': the eddy moves west.

Consider now the transport between two isobars corresponding to layer depths of $H$ and $H + \Delta H$, at latitudes $y_1$ and $y_2$; $\Delta H$ is assumed to be small so the average depth of the layer is $H$. The total southward transport in the upper layer through the area between A and B is then $M_{\text{tot}} = H M'$ which, from eqns (3.4) and (3.6), is $M_{\text{tot}} = g H \Delta \rho \Delta h f(y_1) = \rho_0 g H \Delta h f(y_1)$, (3.7) where $\Delta h = \Delta \rho \Delta H / \rho_0$ is the steric height difference between A and B, and $f(y_1)$ is the Coriolis parameter at the latitude $y_1$ of A and B.
Teleconnections in EBUS:
a focus on oceanic coastally trapped waves

\[ M_{\text{tot}} = \frac{gH \Delta \rho \Delta H}{f(y_1)} = \frac{\rho_0 gh \Delta h}{f(y_1)} \]

\[ M_{\text{tot}} = \frac{gH \Delta \rho \Delta H}{f(y_2)} = \frac{\rho_0 gh \Delta h}{f(y_2)} \]

\[ gH \Delta \rho \Delta H \left( \frac{1}{f(y_1)} - \frac{1}{f(y_2)} \right) = gH \Delta \rho \Delta H \frac{\beta \Delta y}{f^2(y_1)} \]

\[ \rho_0 \frac{\partial H}{\partial t} = \frac{gH \Delta \rho \Delta H}{f^2(y_1)} \frac{\beta \Delta y}{\Delta x} \frac{\Delta y}{\Delta y} \]

\[ \frac{\partial H}{\partial t} = \frac{\beta gH}{f^2(y_1)} \frac{\Delta \rho}{\rho_0} \frac{\partial H}{\partial x} \]

\[ c_R(y) = \frac{\beta gH (\Delta \rho / \rho_0)}{f^2(y)} \]

Thank you Mrs Tomczak & Godfrey
Atlantic tele-connections: a tri-dimensional schematic
Equatorial and coastal waves in satellite SSH
A focus on intra-seasonal waves (1-3 months)

Intraseasonal SLA (T/P) from Polo et al (2008)

Lag correlations (0.2 contours) between T/P SLA (*) and SLA in the whole basin

Kelvin Wave:
- propagate from western equator to 12°N and S at the african coasts
- ~2 months period, v ∈ [1.5, 2.1] m/s
- remote forcing in the coastal upwelling areas

Intraseasonal SLA (T/P) from Polo et al (2008)

Lag correlations (0.2 contours) between T/P SLA (*) and SLA in the whole basin
Equatorial and coastal waves impacts on SST

A significant fraction of the SST variability is forced by CTW

1. Peru-Chili

10-30% of intra-seasonal variability (model)

Illig et al. 2014

2. Canary

3. Benguela

80% interannual variability (model)

Spectral analysis (wavelet) of observed Sea Level Anomalies (SLA)

Bachèlery et al. 2015

Figure 9. Intraseasonal variability (40-90 days) ratio (%) of variance between ROMS simulation and ROMS as a function of latitude for the SST (red, left scale) and the depth of the 15°C isotherm (d15, blue, right scale) averaged in a 0.5° coastal band.
Equatorial and coastal waves impact on SST: Atlantic

How much SST is impacted by SSH anomalies? (waves + local wind forcing)

0.4-0.5°C / cm in EBUS fronts

Middle boxes: Regression along the Northern and Southern wave tracks respectively c) and d) for the Model (blue curve) and Observation (red curve).
Lower boxes: Correlations along the wave tracks. Note that the seasonal cycle is removed before computing the regression and correlation.

=> model experiment
Methodology : Model used and experiments

- Model :
  - DRAKKAR ¼°, Tropical Atlantic configuration (30°N-30°S, 60°W-20°E), 46 vertical levels (6m resolution in surface) : ATLTTROP025, coll. Charles Deltel (LOCEAN)
  - atmospheric forcing : DFS4 (Brodeau et al, 2007) from ERS wind stress and CORE data

- Goal :
  Discrimination of remote and local effect of wind stress on temperature evolution

- Methodology and Experiments :
  - « wind burst simulation » : climatological forcing + westerly wind burst : WWB
  - difference between both runs

-Diagnostic tool : mixed layer heat budget :

\[
\partial_t T - Q \approx -u \partial_x T - v \partial_y T + \partial_z (K \partial_z T) \approx \partial_t T_{ocean}
\]
**Methodology**: Model used and experiments

**westerly wind burst (WWB)**

- from 5°N to 5°S, Brazilian coast to 10°W
- 2 months period, only positive phase
- phase speed of the first and second baroclinic mode in tropical Atlantic = 2.5 and 1.4 m/s (Illig et al, 2003)
- \( \lambda = 40° \) of longitude (deduced from observed wind stress variance); \( T = 2 \) months -> \( c = \lambda / T \approx 1.6 \) m/s: combination of first and second modes at minimum
- wind burst imposed in January (to avoid TIWs)
Results: Simulated coastal waves

SSH anomaly (cm): wbst - clim
Results: Simulated coastal waves

SSH anomaly (cm): wbst - clim
Results: Simulated coastal waves

SSH anomaly (cm): wbst - clim
Results: Simulated coastal waves

SSH anomaly (cm): wbst - clim
Results: Simulated coastal waves

SSH anomaly (cm): wbst - clim
Results: Simulated coastal waves

SSH anomaly (cm) : wbst - clim
Results: Simulated coastal waves

SSH anomaly (cm): wbst - clim
Results: Simulated coastal waves

SSH anomaly (cm): wbst - clim
Results: Simulated coastal waves

SSH anomaly (cm): wbst - clim
Results: Simulated coastal waves

SSH anomaly (cm): wbst - clim

TIME: 16-FEB 22:57
Results: Simulated coastal waves
Results: Simulated coastal waves

SSH anomaly (cm) : wbst - clim
Results: Simulated coastal waves

SSH anomaly (cm) : wbst - clim
Results: Simulated coastal waves

SSH anomaly (cm): wbst - clim
Results: Simulated coastal waves

SSH anomaly (cm): wbst - clim
Results: Simulated coastal waves

SSH anomaly (cm): wbst - clim
Results: Simulated coastal waves

SSH anomaly (cm) : wbst - clim
Results: Simulated coastal waves

SSH anomaly (cm): wbst - clim
Results: Simulated coastal waves
Results: Simulated coastal waves

ATLTROP025-WWB and T/P SSH (m) along equator and coastal trajectories

Wave: propagation from 30°W-eq to 12° N and S; \( v \approx 1.9 \text{ m/s} \)
Very similar to observed Kelvin wave
Thermal impact of a January equatorial wave (model)

Climatological February SST (°C) and contours D18 (m) ATLTROP025

14/03

27/02

22/02

SST (°C) and contours SSH (cm) ATLTROP025-WWB
Results: Thermal impact of coastal waves: Angola upwelling

\[
\frac{dSST}{dt} = \frac{1}{h} \frac{\partial}{\partial t} (T - T_{z=h}) - \frac{1}{h} (K_z \frac{\partial T}{\partial z})_{z=h} + \frac{Q^* + Q_s(1 - f_{z=h})}{\sigma_0 C_p h}
\]

\[\partial_t T_{\text{ocean}} = \langle u \cdot \frac{\partial}{\partial x} T \rangle - \langle v \cdot \frac{\partial}{\partial y} T \rangle + \langle D_i(T) \rangle\]

Subsurface fluxes:
- Horizontal advection
- Zonal advection
- Meridional advection

Mixed layer heat budget trends (°C/day), and integrated terms (°C)

[Graph showing temperature trends and advection contributions]

1.5°C
1°C
0.5°C
-0.5°C

75%
25%
(70% + 30%)
Thermal impact of coastal waves: Angola upwelling

Mixed layer heat budget trends (°C/day), and integrated terms (°C)
Thermal impact of coastal waves: Guinea Gulf upwelling

∂tT ocean
Subsurface
Horizontal advection
Zonal advection
Meridional advection

Total (upper) and integrated (lower) mixed layer heat budget trends (°C/day),
3.5°N, 6°E - 1°W@ave
**Results** : Thermal impact of coastal waves: Senegal upwelling

\[
\delta tT_{\text{ocean}}
\]

- **Subsurface**
- **Horizontal advection**
- **Zonal advection**
- **Meridional advection**

Total (upper) and integrated (lower) mixed layer heat budget trends (°C/day), 11°N - 18°N@ave
Equatorial and coastal intra-seasonal waves in satellite SSH: Need to extract a typical wave...

Figure 11: Diagrammes de Hovmöller pour les anomalies intra-saisonnières de SSH (m), pour l'équateur et (à gauche) la côte nord-africaine et (à droite) la côte sud-africaine pour la période 2008-2016. Le premier trait noir sur les deux panneaux montre la frontière entre l'équateur et les côtes ouest-africaines. Le deuxième trait du panneau de gauche représente la position de la bouée Mélax et sur le panneau de droite la position du Benguela.

IV.3 Composite lagué le long de la trace d’ondes

IV.3.1 Composite de l'anomalie de la SST

Les figures 12 et 13 représentent les diagrammes de Hovmöllers des composites de l'anomalie de la SSH, de la SST et celle du stress de vent méridien pour la période 2008-2016. Nous avons effectué un lissage sur les contours en moyennant sur cinq points temporels pour plus de visibilité. On constate que la SST affiche un réchauffement net des eaux de surface dans les zones d'upwellings pour la période 2008-2016. Le signal dans la zone d'upwelling sénégalaise est moins intense qu'en Angola au passage de l’onde de Kelvin. Le composite de la SST lagué de -8 à 4 le long de l’Atlantique équatorial et la côte est négatif entre lag-8 et lag0 à la position de la bouée Mélax avec une valeur minimale comprise entre -0,36°C et -0,12°C. De plus l'anomalie de la SSH et de la tension de vent méridional sur la même période sont respectivement environ égales à -1,4 cm et -2.10⁻³ N/m². Par contre au lag0 au moment de passage de l’onde de Kelvin de downwelling, on a la SST qui est positive environ égale à 0,12°C et qui augmente progressivement pour atteindre Badara SANE

=> Composite wave reaching the north or south EBUS fronts
Composite intra-seasonal downwelling CTWs reaching the EBUS fronts

SSH, SST
Composite intra-seasonal downwelling CTWs reaching the EBUS fronts

SSH, SST, meridional Wind at the EBUS fronts

Figure 20: Séries temporelles du composite de l'anomalie de la SSH, de la SST et celle du stress de Vent méridien au point de la bouée Mélax (panneau d’en haut) et au niveau du front Benguela-Angola (panneau d’en bas).

IV.4 Étude de cas coïncidant avec la période de la Bouée MELAX

- Variabilité spatiale

La figure 21 nous montre que l’année 2015 est marquée par un début d’une anomalie de SSH positive associée à une onde de downwelling en avril et en septembre et d’une anomalie de SSH négative associée à une onde d’upwelling en mi-mars et mi-mai qui se propagent le long de

WIND IN PHASE with the WAVES!
Composite intra-seasonal downwelling CTWs reaching the EBUS fronts

SSH, SST, Wind at the EBUS fronts

Propagation of the wind! Particularly the meridional component
Composite intra-seasonal downwelling CTWs reaching the EBUS fronts

Wind field anomaly resembling an African Easterly Wave
Conclusion on the effect of an intraseasonal wave

- idealized winter downwelling intraseasonal wave similar to observed ones (amplitude, phase speed, pathways, etc)

- coastal downwelling Kelvin waves (~3cm) in January responsible of ~+ 1.5°C SST variation in coastal upwellings areas on 10° extension, comparable to observations

- similar thermal impact of the wave over the Benguela and Senegal upwelling fronts:
  
  2/3 horizontal advection + 1/3 vertical diffusion

- opposite effects in the Gulf of Guinea upwelling
  
  3/4 vertical diffusion - 1/4 horizontal advection

No universal effect, since it depends on the background state

Then...

Local wind forcing intra-seasonal fluctuations constructively or destructively interact...

...along Africa, the mean (composite) wave events appear to have constructive wind events associated to African easterly waves coming from the continent