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# Preliminary study on the variations of barrier layer in the western Pacific and its impacts on tropical cyclones

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# Abstract

A great number of previous researches have revealed that the upper ocean structure plays an important role in tropical cyclone’s intensification. Different kinds of pre-existing oceanic condition (warm/cold core ring, TCHP) can lead TC to different intensity development.

The ocean barrier layer (BL) and its influence on TC intensity is being discussed recently, and many conclusion which based on observation or simulation affirm that the existence of thick barrier layer can effectively reduce TC-induced vertical mixing (i.e. negative feedback effect).

**The main result of this project generalizes the temporal and spatial change of BL in Northwestern Pacific Ocean region from 1981 to 2010, and the TC-BL interaction in the period of 1996-2010.**

# Introduction

<u>Ocean Barrier Layer and Barrier Layer Thickness (BLT)</u>

Barrier layer thickness (BLT) is defined as the difference between isothermal layer depth (ILD) calculated from temperature and mixed layer depth (MLD) calculated from density.

**BLT = ILD - MLD**

Thus the temperature gradient in barrier layer is rarely small, while the water density is **controlled by salinity**.

**The gradient of density is relatively large in barrier layer.**

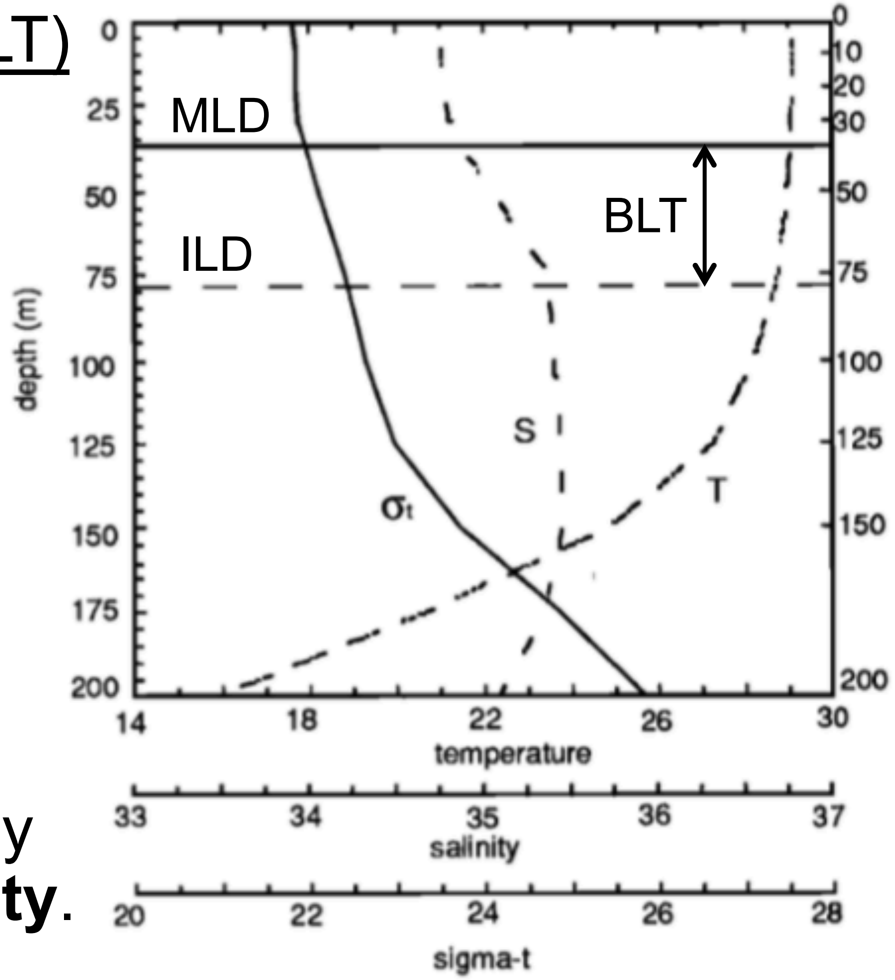



Fig.1 An example profile of the BLT. (Sprintall and Tomczak 1992)

# Richardson Number and Dynamic Stability

Richardson number : $\boxed{R_i \equiv \dfrac{gE}{(\partial u/\partial z)^2}}$

$R_i > 0.25$ Stable
$R_i < 0.25$ Velocity Shear Enhances Turbulence

where $E = -\dfrac{1}{\rho}\dfrac{d\rho}{dz}$ is the *stability* of the water column.

Since the $\dfrac{d\rho}{dz}$ is relatively large in barrier layer, the $R_i$ which related to the stability is also large.

Large $R_i$ will make the water column more stable, **reducing the entrainment cooling effect.**

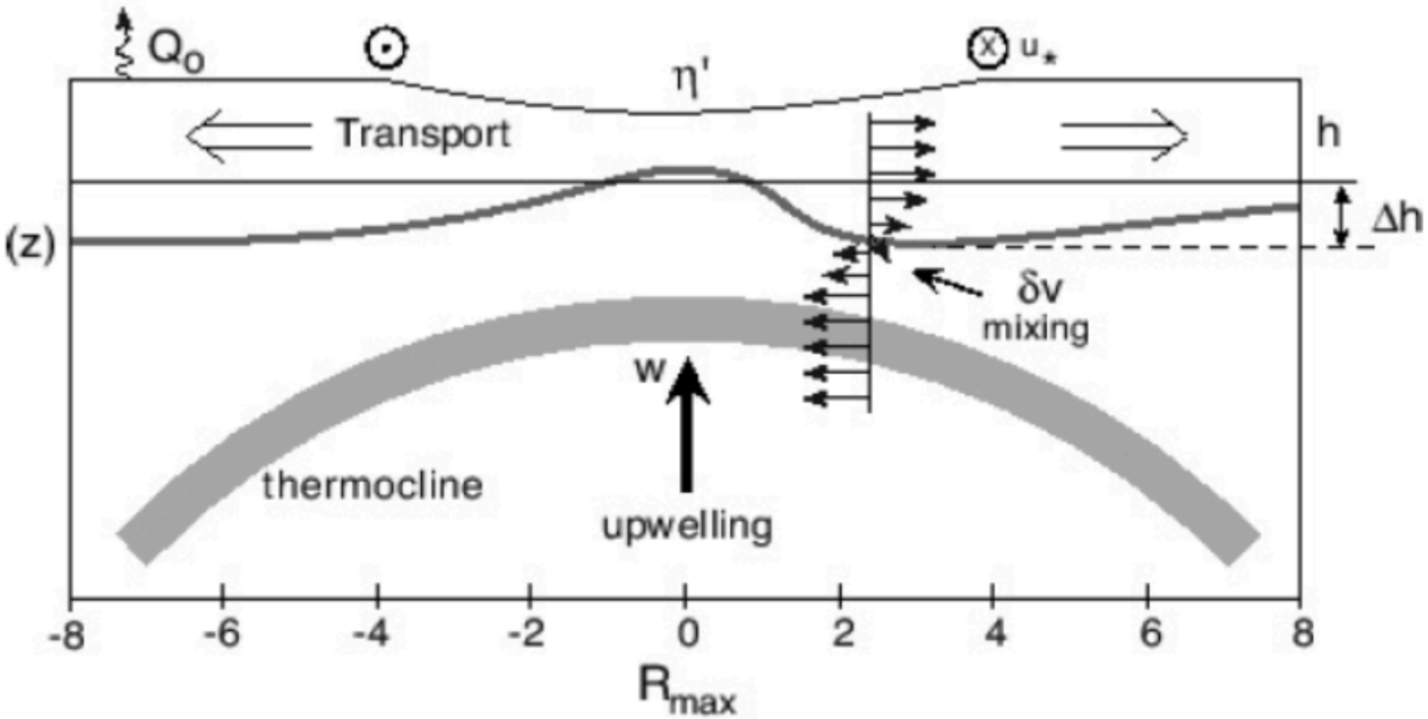



Fig.2 Physical processes of the upper ocean cooling forced by tropical cyclone. (Shay 2010)

# Data

- Ocean Reanalysis System 4 (ORAS4)

The ORAS4 data is provided by ECMWF, which includes several monthly mean physical variables (temperature, salinity, velocities, isothermal/mixed layer depth). Its temporal coverage is from 1958 to present, and spatial coverage is 1°x1° global grids.

- HYCOM + NCODA Global 1/12° Reanalysis (GLBu0.08)

HYCOM+NCODA GLBu0.08 daily data range is from Aug, 1995 to Dec, 2012, and its spatial resolution is about 0.08°x0.08° global grids. Data includes physical variables such as temperature, salinity, velocities, heat fluxes etc. with 40 vertical levels.

- Tropical Cyclone Best Track

The TC best track data is obtained from Joint Typhoon Warning Center (JTWC) . The data includes TC center position (per 6hrs), maximum wind speed, minimum sea level pressure etc.

# Methodology

Use the temperature and salinity data from ORAS4 / HYCOM+NCODA to calculate the upper ocean density via the Equation of State of Seawater (Gill 1982).

$$\text{Isothermal Layer Depth (ILD)} = H(T_{10}+\Delta T)$$

$$\Delta T = -0.2°C$$

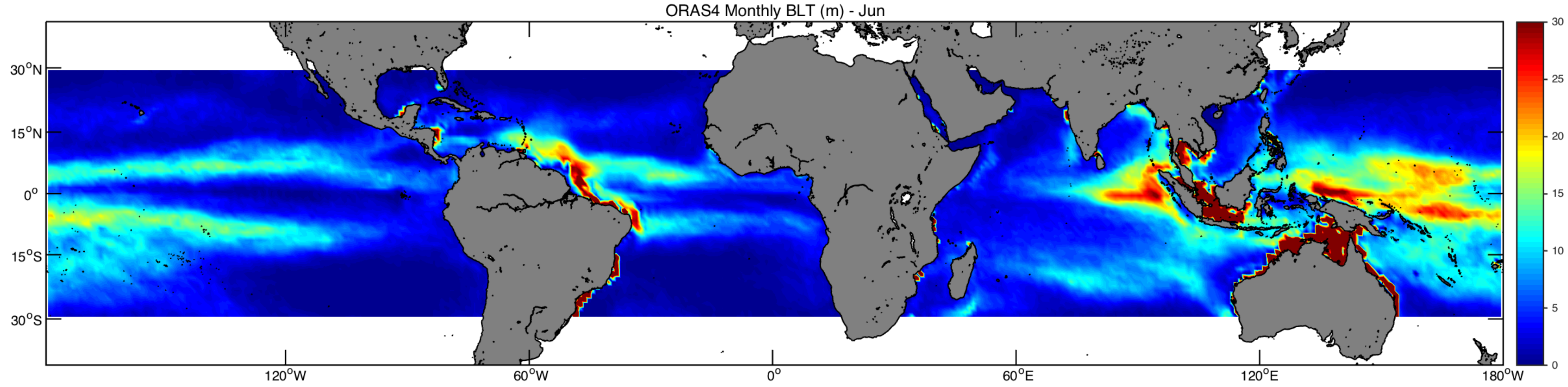
$$\text{Mixed Layer Depth (MLD)} = H(\rho_{10}+\Delta\rho)$$

$$\Delta\rho = \rho(T_{10}+\Delta T, S_{10}, 0) - \rho(T_{10}, S_{10}, 0)$$

$$BLT = ILD - MLD > 0$$

Furthermore, the **Effective BLT** is defined as the BLT ≥ 10m.

# Global Distribution of BLT



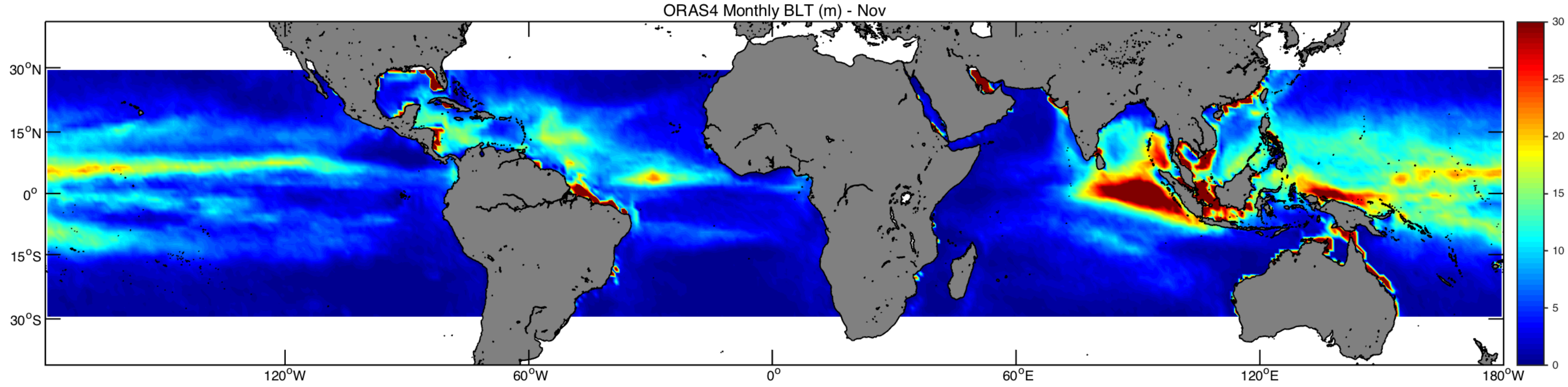
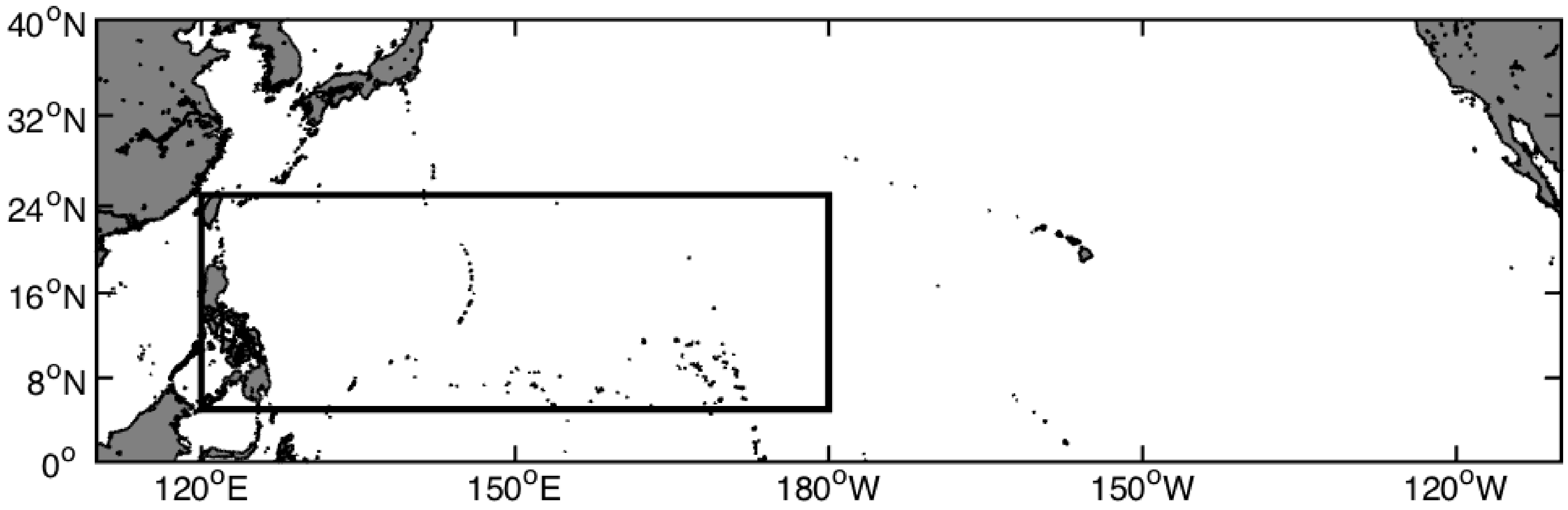




Fig.3 (up) Fig.4 (down) Global (30°N-30°S) monthly mean BLT spatial distribution of Jul (up) and Nov (down).

Obvious variation: **Western Pacific, Indian Ocean, Western Atlantic**

# Main Development Region (MDR)



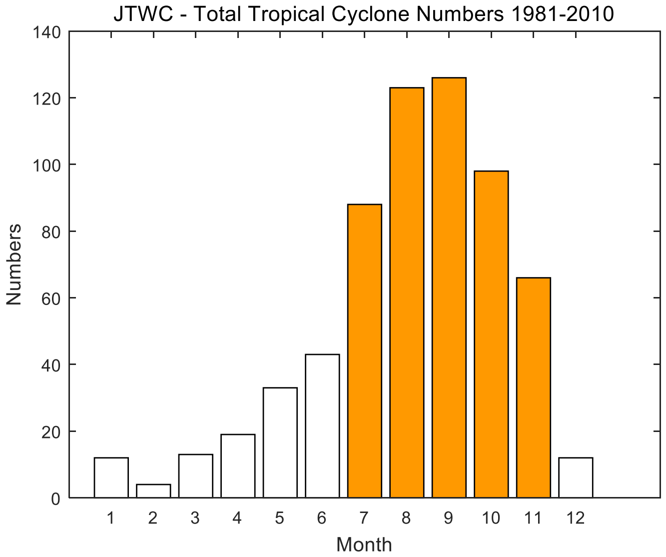




Fig.5 (left) Illustration of TCs main development region. Fig.6 (right) 1981-2010 Statistical numbers of TCs in MDR.

According to the data obtained from JTWC, the main development region (MDR) in northwestern pacific region is defined as the area between 120°E-180°E and 5°N-25°N.

Meanwhile, this research defined Jul-Nov as the TC-prevailing season in MDR.

# Variation of Effective Barrier Layer Area and Depth

The variation of effective barrier layer's area in MDR remains almost the same.

1981-2010: slightly decreasing
2001-2010: slightly increasing

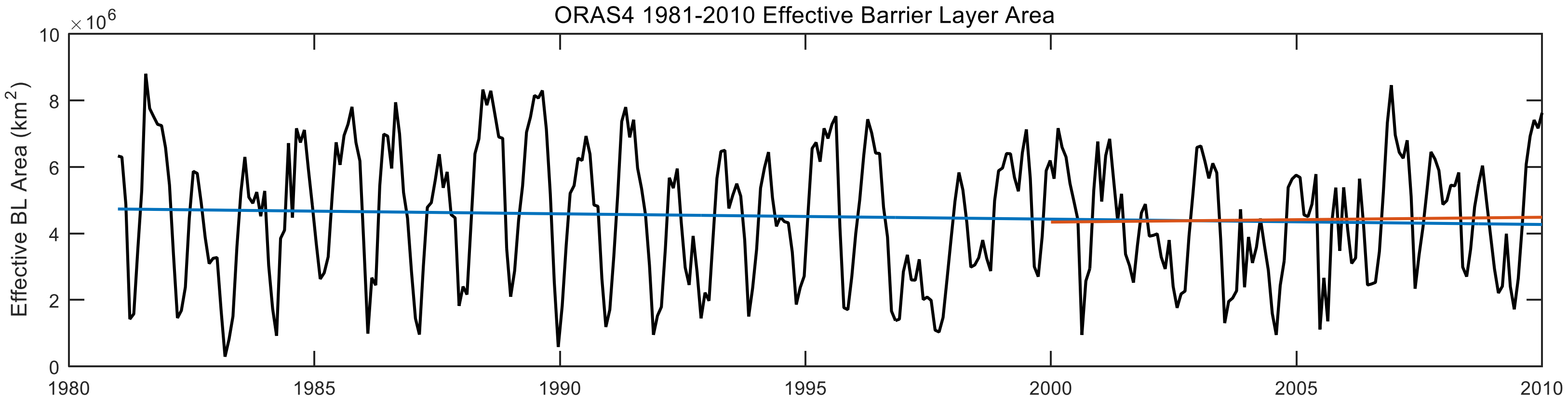



Fig.7 ORAS4 1981-2010 variation of effective BL area.

The variation of effective barrier layer's depth in MDR is relatively increasing.

1981-2010: slightly increasing
2001-2010: obviously increasing

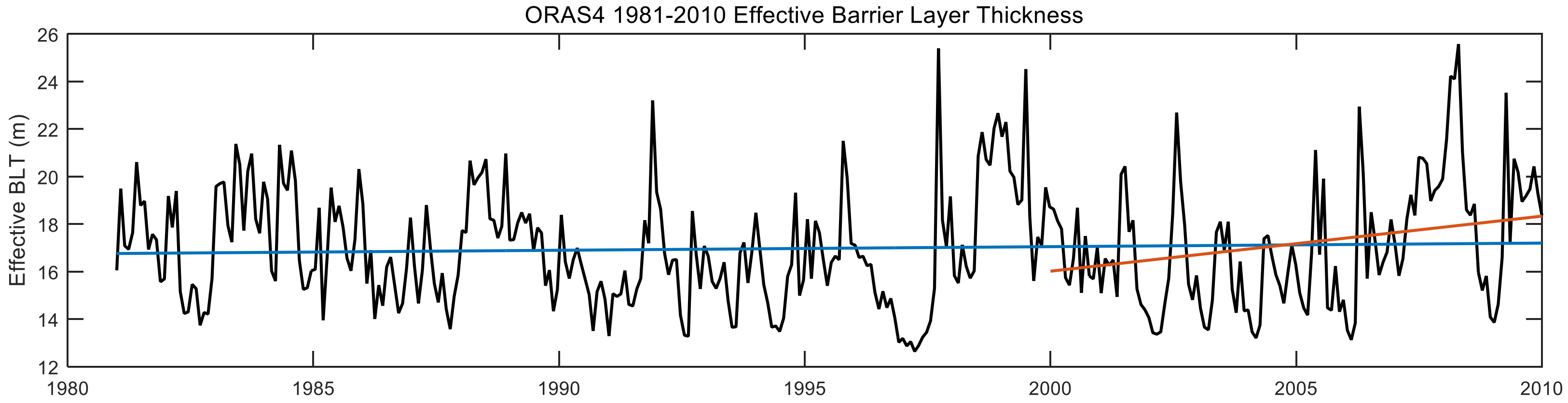
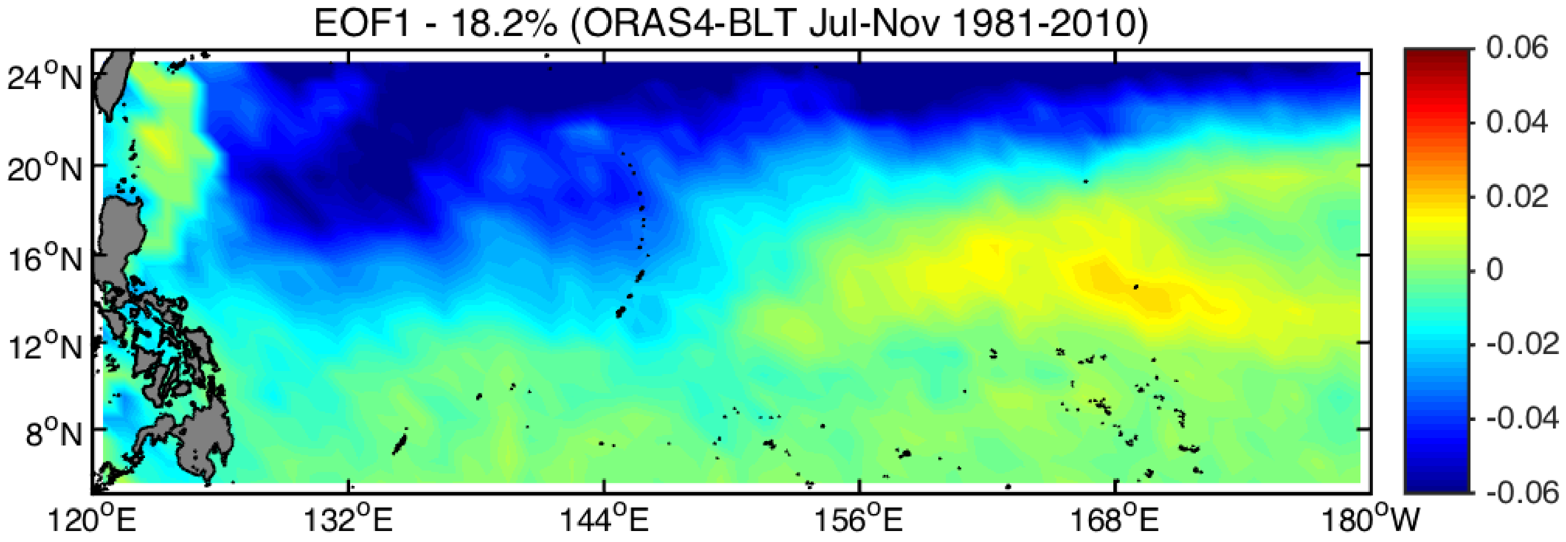



Fig.8 ORAS4 1981-2010 variation of effective BL depth.

# Empirical Orthogonal Function Analysis



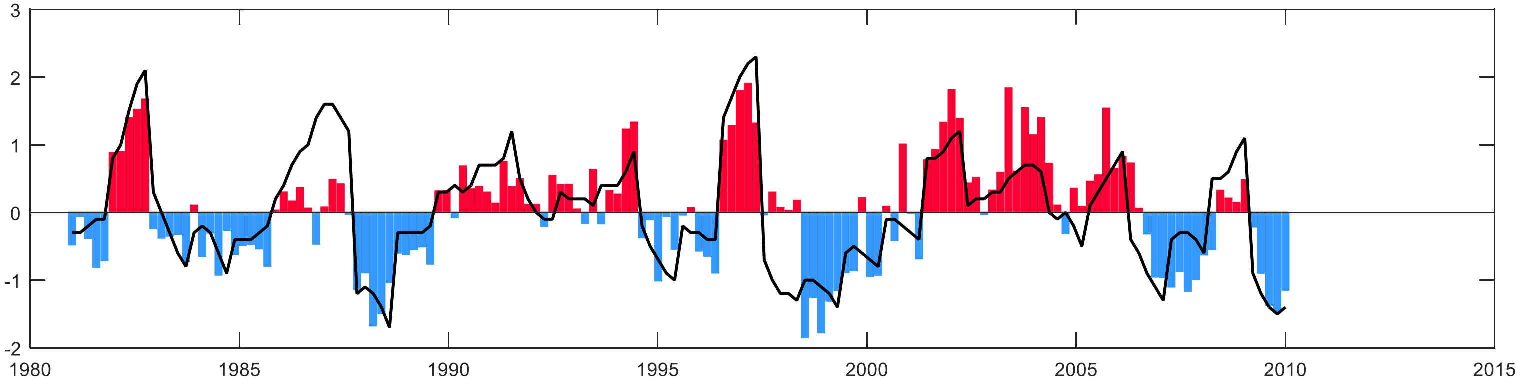
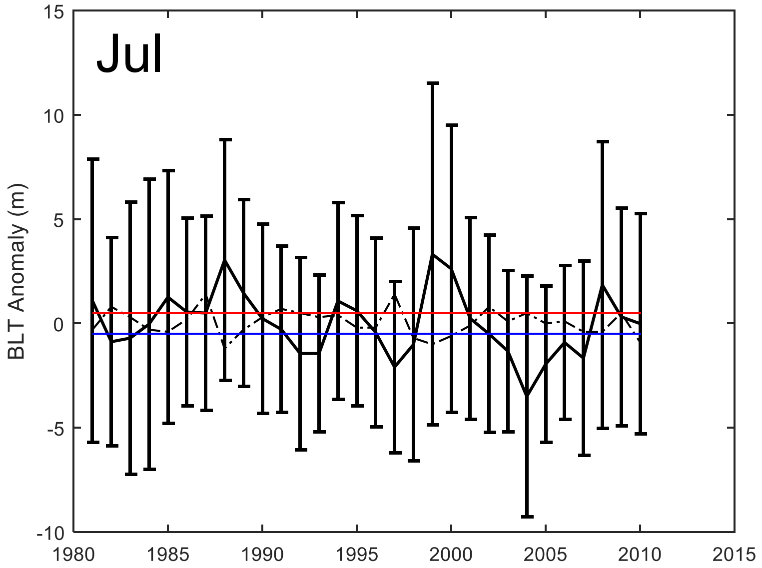



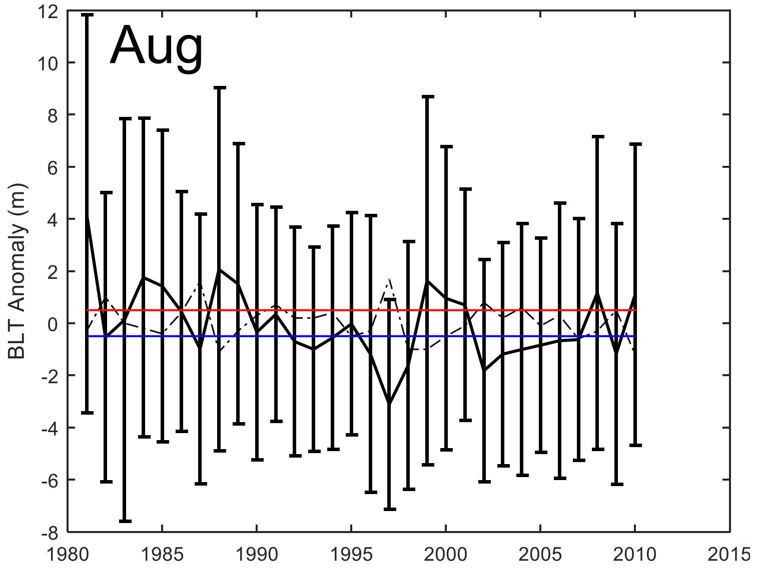

Fig.9 (up) Main development region EOF spatial pattern of the first BLT mode calculated for the TC-prevailing season (Jul-Nov) in the period of 1981-2010.

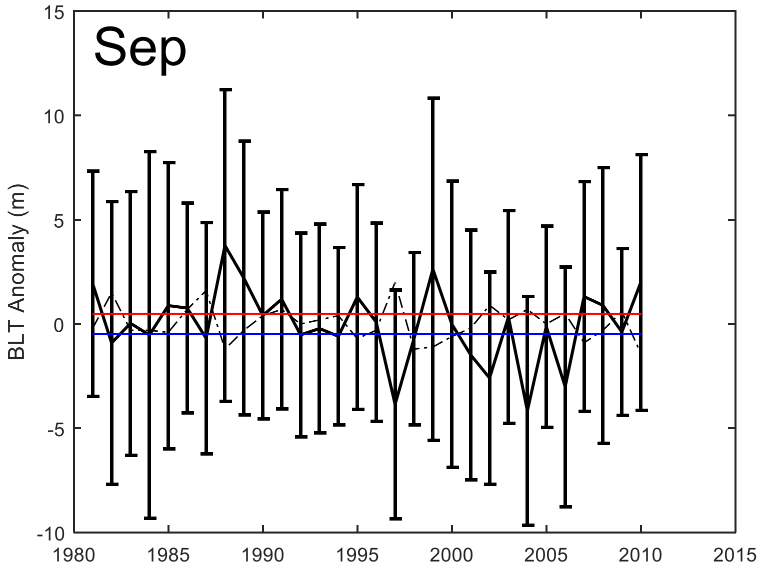
Fig.10 (down) Time series of the principle component associated with the first BLT mode (normalized). Black solid line is the CPC Nino 3.4 index.

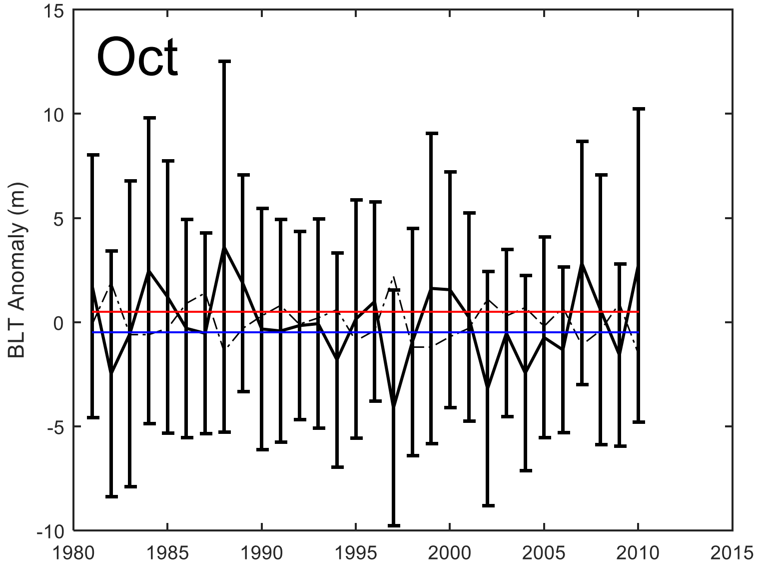
Though the variance explained by the first BLT mode is low (18.2%), its principle component's temporal pattern appears to correspond with the time series of Nino 3.4 index.

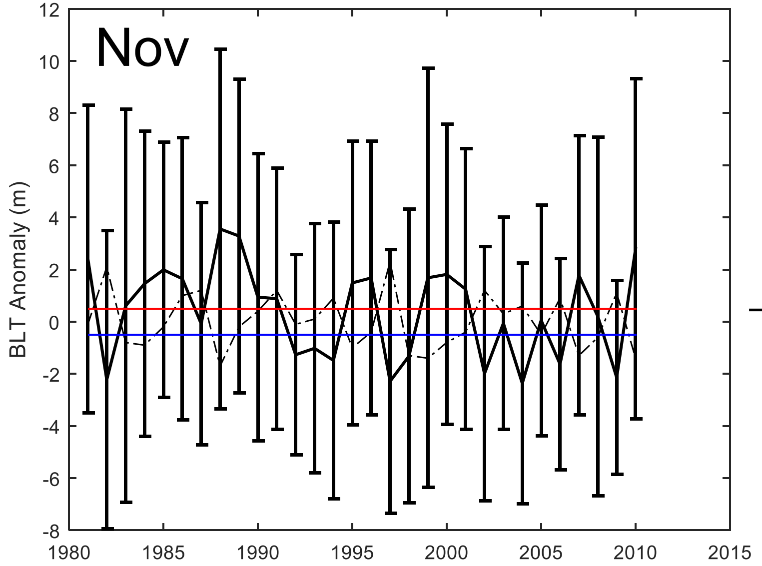
# MDR Region Average BLT Anomaly  Jul-Nov




## Correlation Coefficient of BLT Anomaly and Nino 3.4 Index

| Month | Jul | Aug | Sep | Oct | Nov |
|---|---|---|---|---|---|
| $R_{ENSO}$ | -0.53 | -0.56 | -0.65 | -0.80 | -0.66 |

Fig.11 – Fig.15 Average BLT anomaly (solid line) and CPC Nino 3.4 index (dashed line).

An error bar is one standard deviation. The red and blue line indicate the threshold of Nino or Nina events.

## The average BLTs of each months in MDR (120°E-180°E and 5°N-25°N)

| Month | Jul | Aug | Sep | Oct | Nov |
|---|---|---|---|---|---|
| BLT (m) | 7.85 | 9.44 | 9.57 | 9.79 | 9.24 |

All the average BLTs (except Jul) are close to the definition of effective BLT (10m), and due to the previous page, the thickness is found to **increase in periods of Nina events, on the other hand, it is generally decreasing in the periods of Nino events**.

However, the large standard deviation also tells that the spatial distribution of BLT is quite random. Higher resolution data (i.e. HYCOM) should be applied to find out the probability of TC-BL interaction.

# Spatial Porosity of BLT

While computing the daily data from HYCOM+NCODA in the period of 1996-2010, some problem appeared.

**The frequent changes of spatial distribution of BLT make some researchers name this characteristic as *porosity*.**

A serious problem appears in this project before the discussion on the TC-BL interaction due to the porosity of BLT:

**What Is The Proper Rate of Appearance To Make The BL Effective**

## Definition of the Rate of Appearance (P) and The Following Supposition

Calculate the daily BLTs of each grid in MDR.

$N_{m,n}$ = The number of occurrence of BLs (≥ 10m) on $grid_{m,n}$ during one month

$$P_{m,n} = \frac{N_{m,n}}{\text{Days of the month}}$$

**This study supposed that the higher the $P_{m,n}$ is, the more stable environment the water column provides.**

In the following part, the **$P_{m,n}$ must be larger than 0.2 (≈ 6 or 7 days per month), moreover, the $BLT_{m,n}$ must ≥ 10m** to make the $BLT_{m,n}$ be defined effective in decreasing the TC-induced cooling effect.

# Probability of TC-BL Interaction in 1996-2010

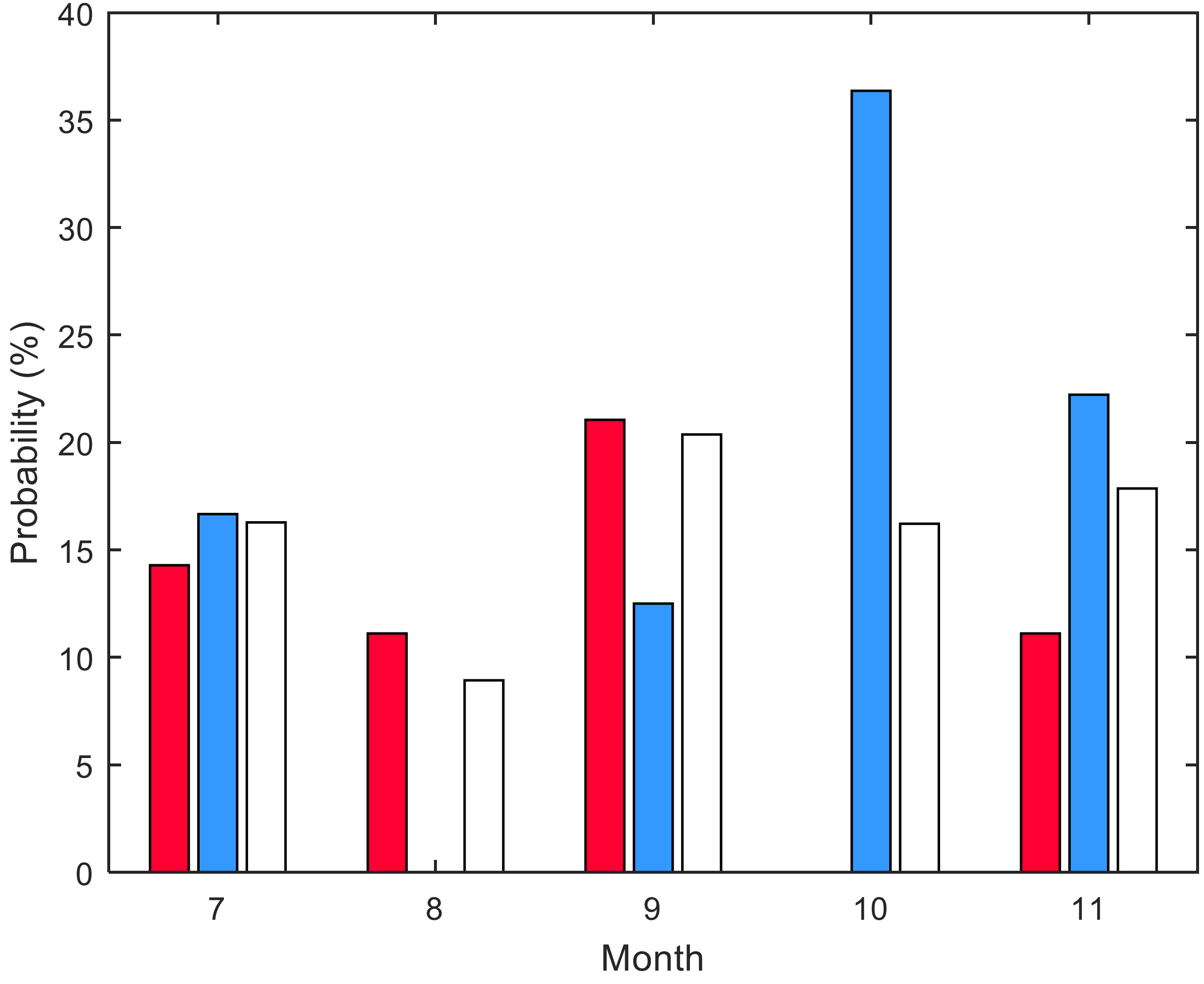



Fig.16 Probabilities of TC-BL interaction during the TC-prevailing season in 1996-2010. The probability of the period of Nino events (red), Nina events (blue) are computed respectively, besides the probability of the total period (white). (TCs in Sep and Oct of 1996 are excluded from calculation due to the lack of HYCOM data.)

According to the JTWC and HYCOM data, the probability of TC-BL interaction are 36% and 22% in Oct and Nov respectively during the period of Nina events.

However, the probability during the period of Nino events are greater than the period of Nina events or the total period (1996-2010) in other months (ex: Aug & Sep).

## The Average Effective BLT (m) Along TC Tracks (1996-2010)

| Month | Jul | Aug | Sep | Oct | Nov |
|---|---|---|---|---|---|
| Nino events | 11.36 | 18.41 | 16.65 | - | 20.80 |
| Nina events | 18.76 | - | 13.80 | 30.40 | 24.34 |

The effective BLTs touched by tropical cyclones are thicker in Nina events broadly, with few exception.

The variation of average thickness seems to have positive correlation with the probability of TC-BL interaction.

Moreover, the HYCOM surface temperature data were calculated roughly for **the comparison of sea surface cooling effect with / without barrier layer (≥ 10m).**

<u>Methods</u>

The tropical cyclone center position (per 6hrs) is adopted as the origin, and the average SST of surrounded area (0.24° x 0.24°) is adopted on the day of TC and the day after.

$$\Delta T = SST_{day+1} - SST_{day}$$

<u>Result</u>

$$\Delta T_{average} \text{ with barrier layer} = -0.137\ °C$$
$$\Delta T_{average} \text{ without barrier layer} = -0.181\ °C$$

Though the difference is small (0.044°C), the phenomenon of surface temperature inversion mentioned by previous study (Balaguru 2012) still appeared in few BLT region. The average temperature inversion ($\Delta T_{inversion}$) = 0.13°C of these few region.

# ENSO Events BLT Anomaly Composites (HYCOM)

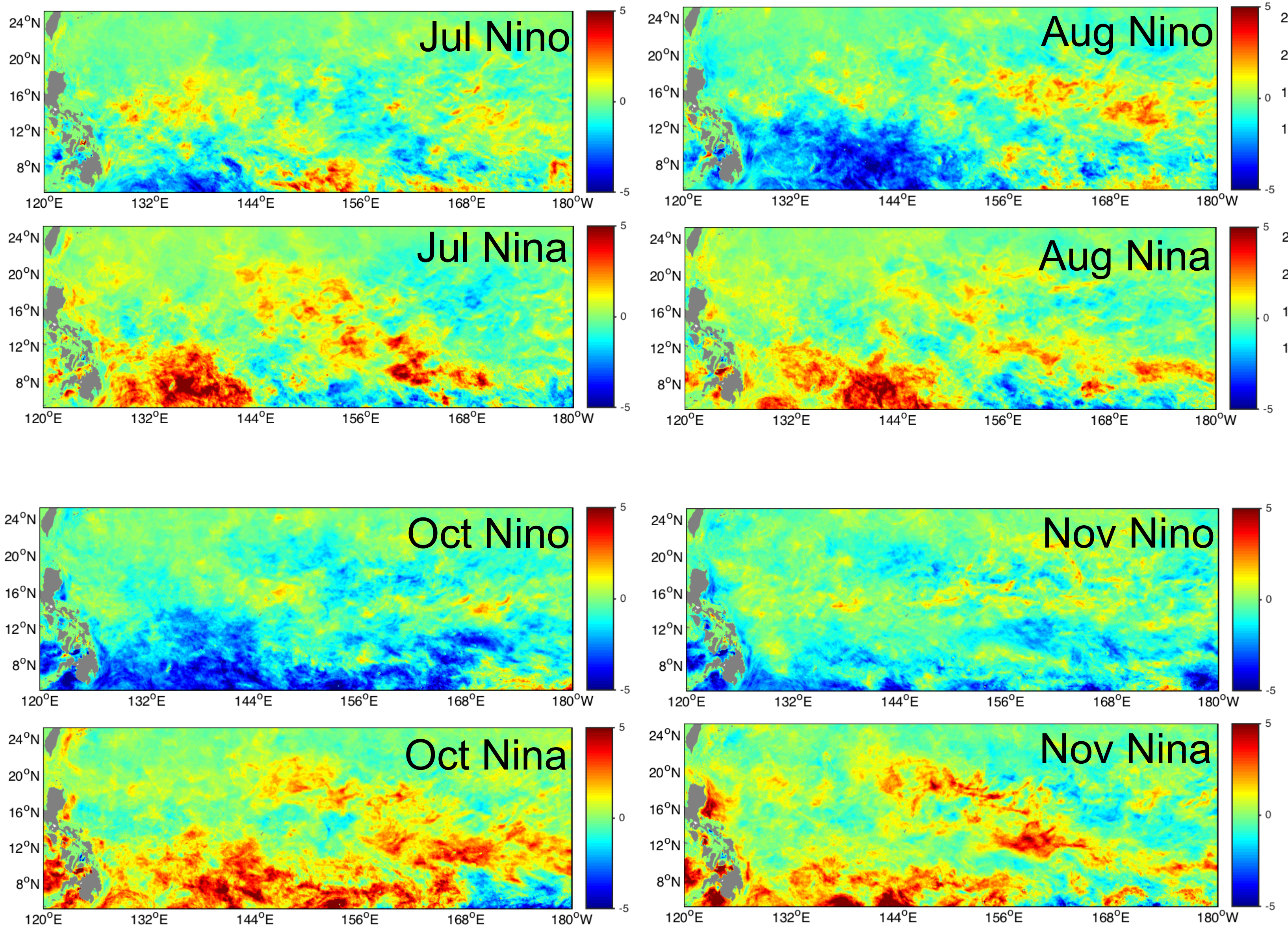



Fig.17 – Fig.26 The BLT anomalies composites of Nino and Nina events during the TC-prevailing season in 1996-2010.

The color bar range is from -5m to 5m.

# Probable Mechanisms of BL Formation

According to the previous studies (Cronin and McPhaden 2002), there are four dominant mechanisms of BL formation, which are:
**(1) horizontal advection term, (2) tilting term, (3) stretching term, and (4) rainfall term**.

$$S_{zt} = -\underset{(1)}{\vec{U} \cdot \nabla S_z} - wS_{zz} - \underset{(2)}{\vec{U}_z \nabla S} - \underset{(3)}{w_z S_z} - \underset{(4)}{\overline{(w'S')}_{zz}}$$

This research found that the **rainfall term** seems to lead the spatial distribution of BLT in MDR during the Nino events, **not in Nina events however**.
Nevertheless, the robust mechanisms should be investigate strictly in future work.

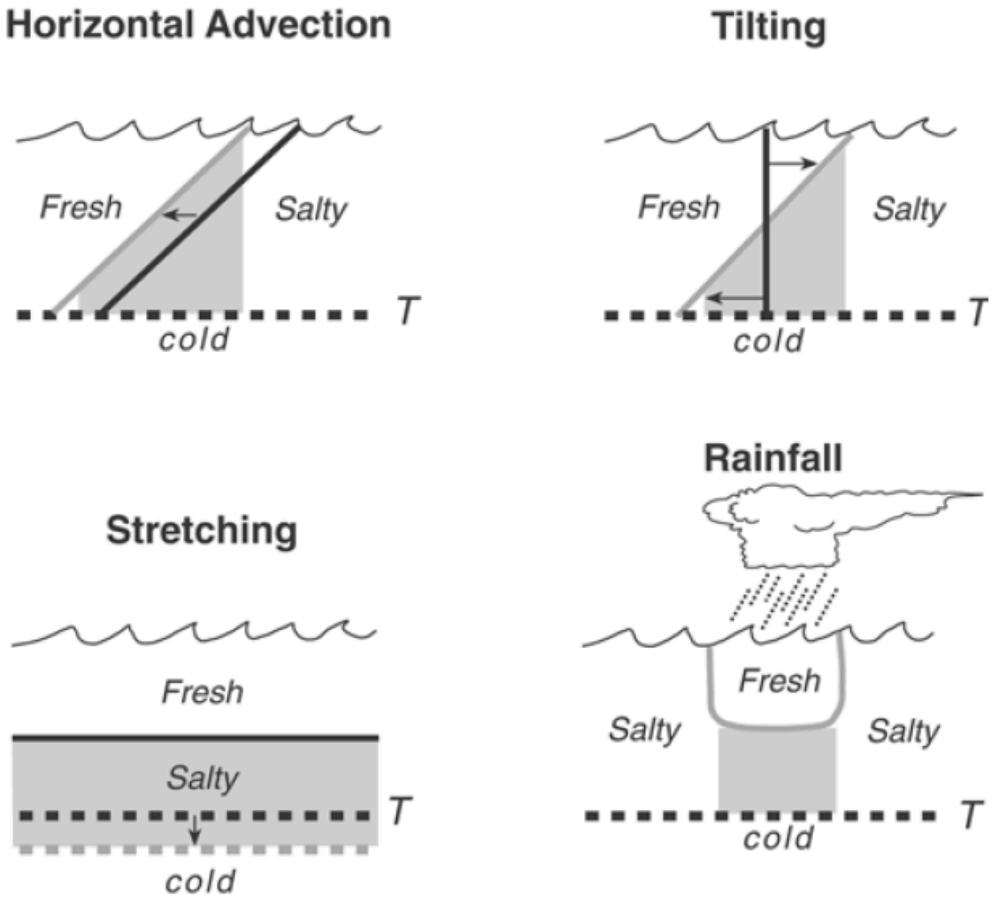



Fig.27 Mechanisms of barrier layers' formation corresponding to different term. (Cronin and McPhaden 2002)

# Conclusion

Barrier layer Thickness may be **the proxy of stability** of the regional water column.

The average of effective BLT in MDR is increasing in recent decade and **negatively correlated with ENSO events**.

The region of high variation of BLT almost centralize on the southwestern part of MDR, and this inter-annual variability may influence significantly on Philippines than on Taiwan.

Probability of TC-BL interaction in Oct and Nov during the period of Nina events is higher than normal time as well as Nino events, which may be a factor for some extraordinary intense tropical cyclone cases.

# Future Work

The numerical model (ocean model / coupled air-sea model) is suggested to be used for simulating the more realistic dynamic mechanism between tropical cyclone and barrier layer.

Find out the dominant mechanism of regional barrier layer formation, and its contribution to the stability of water column.

Determine the more specific definition of the porosity of BLT, and quantify the capability of different barrier layer (thickness, area, gradient of density, etc.) for decreasing the sea surface temperature cooling effect.

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