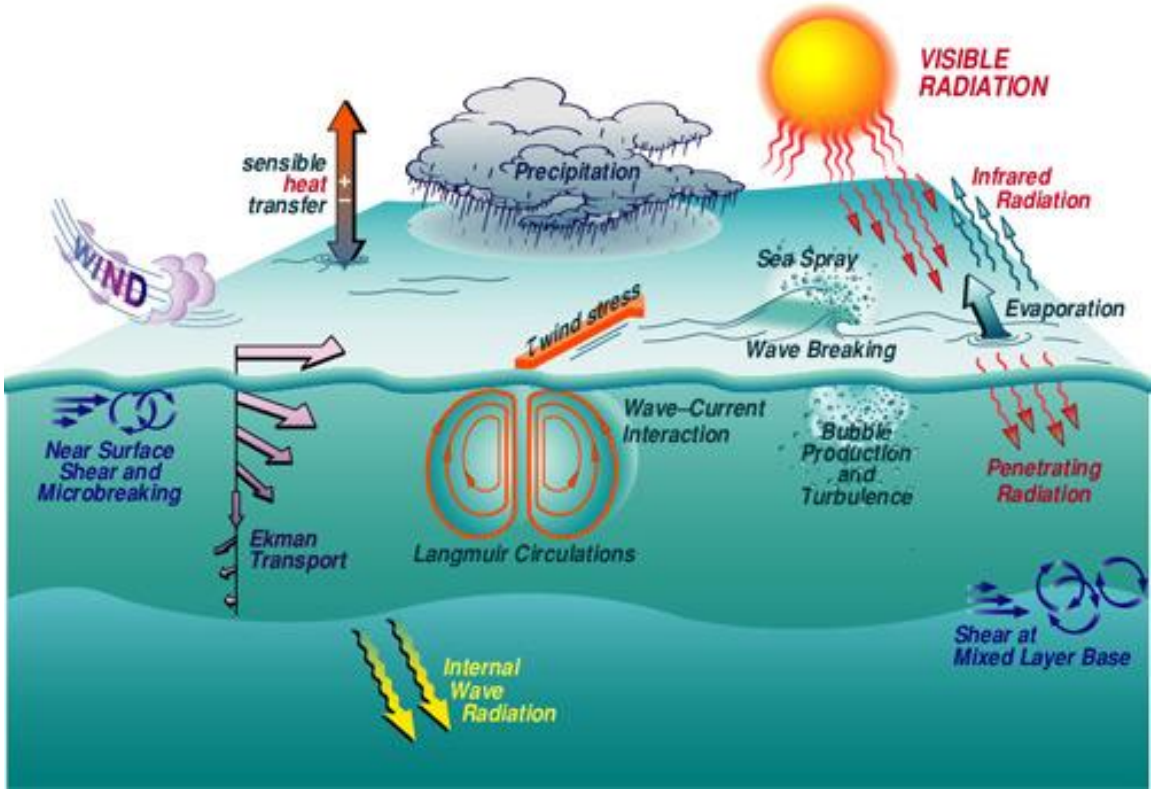
Objective Determination of Global Ocean Mixed Layer Depth

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Importance of mixed layer depth in upper ocean dynamics and climate change



From the website: www.locean-ipsl.upmc.fr/~cdblod/IMAGES/mixed_...

Outline

- (1) Existing Methods → Mixed Layer Depth from (T, S) Profiles
- (2) New Objective Method
- (3) Global Mixed Layer Data Set

Various Criteria for Determining H_{mix} (de Boyer Montegut et al., 2004, JGR)

Author and Area Studied	Profiles	MLD Threshold Criterion	Z_{ref}	Criterion Choice
Sprintall and Roemmich [1999], Pacific Ocean	ind	$\Delta T = 0.1°C$ $\Delta\sigma_\theta = \frac{\partial\sigma_\theta}{\partial T}\Delta T$ with $\Delta T = 0.1°C$	10 m	direct observation of more than 1000 profiles
Kara et al. [2000b], Global Ocean	ave	$\Delta T = 0.8°C$ $\Delta\sigma_\theta = \sigma_\theta(T + \Delta T, S) - \sigma_\theta(T, S)$ with $\Delta T = 0.8°C$	10 m	statistical comparison with Ocean Weather Station data
Monterey and Levitus [1997], Global Ocean	ave	$\Delta T = 0.5°C$ $\Delta\sigma_\theta = 0.125$ kg m^{-3}	0 m	$\Delta\sigma_\theta$ corresponds to water mass characteristics of subtropical mode water in North Atlantic ΔT corresponds to $\Delta\sigma_\theta$ within 17 to 19°C and $S = 35$ *PSU*
Brainerd and Gregg [1995], Pacific Ocean	ind	$\Delta\sigma_\theta = 0.05$ to 0.5 kg m^{-3}	0 m	direct observation of overturning length
Suga et al. [2004], North Pacific	ind	$\Delta\sigma_\theta = 0.125$ kg m^{-3}	10 m	arbitrary
Thomson and Fine [2003], North Pacific	ind	$\Delta\sigma_\theta = 0.01$ to 0.03 kg m^{-3}	2.5 m	arbitrary
Weller and Plueddeman [1996], North Pacific	ind	$\Delta\sigma_\theta = 0.03$ kg m^{-3}	10 m	arbitrary
Schneider and Müller [1990], Tropical Pacific	ind	$\Delta\sigma_\theta = 0.01$ or 0.03 kg m^{-3}	2.5 m	corresponds to subjective estimate of MLD
Obata et al. [1996], Global Ocean	ave	$\Delta T = 0.5°C$	0 m	arbitrary
Thompson [1976], North Pacific	ind	$\Delta T = 0.2°C$	3 m	arbitrary
Spall et al. [2000], North Atlantic	ind	$\Delta T = 0.5°C$	0 m	arbitrary
Foltz et al. [2003], Tropical Atlantic	ind	$\Delta T = 0.5°C$	0 m	arbitrary
Rao et al. [1989], Indian Ocean	ind	$\Delta T = 1°C$	10 m	arbitrary

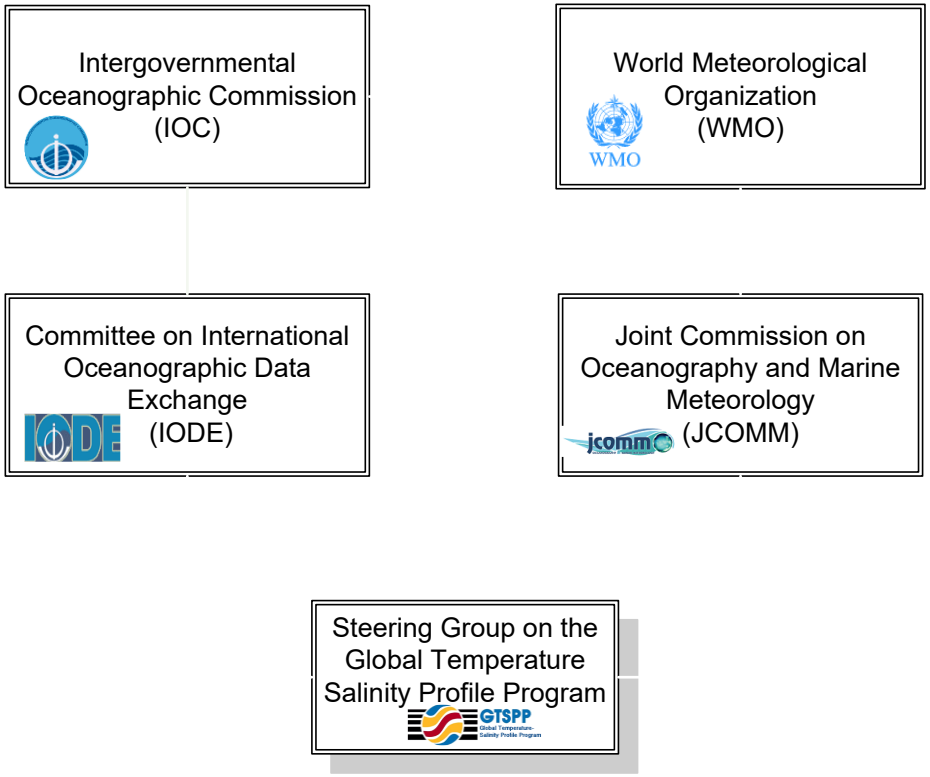
[a]The type of profiles investigated by the author is also mentioned, "ind" for individual and "ave" for monthly averaged profiles, and the way they choose their criterion.

How reliable of the existing methods to determine the mixed layer depth?

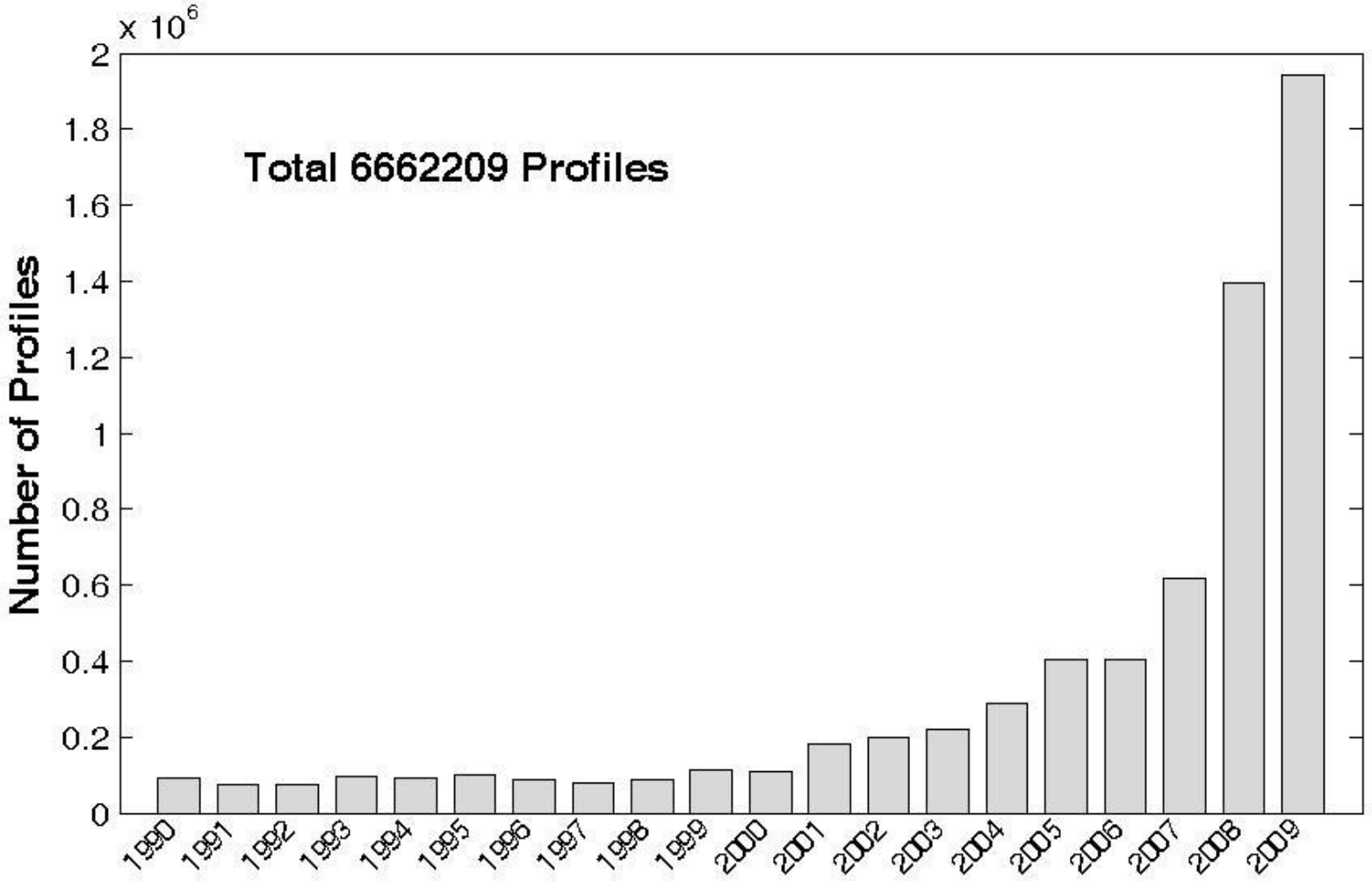
GTSPP

GTSPP = Global Temperature Salinity Profile Program

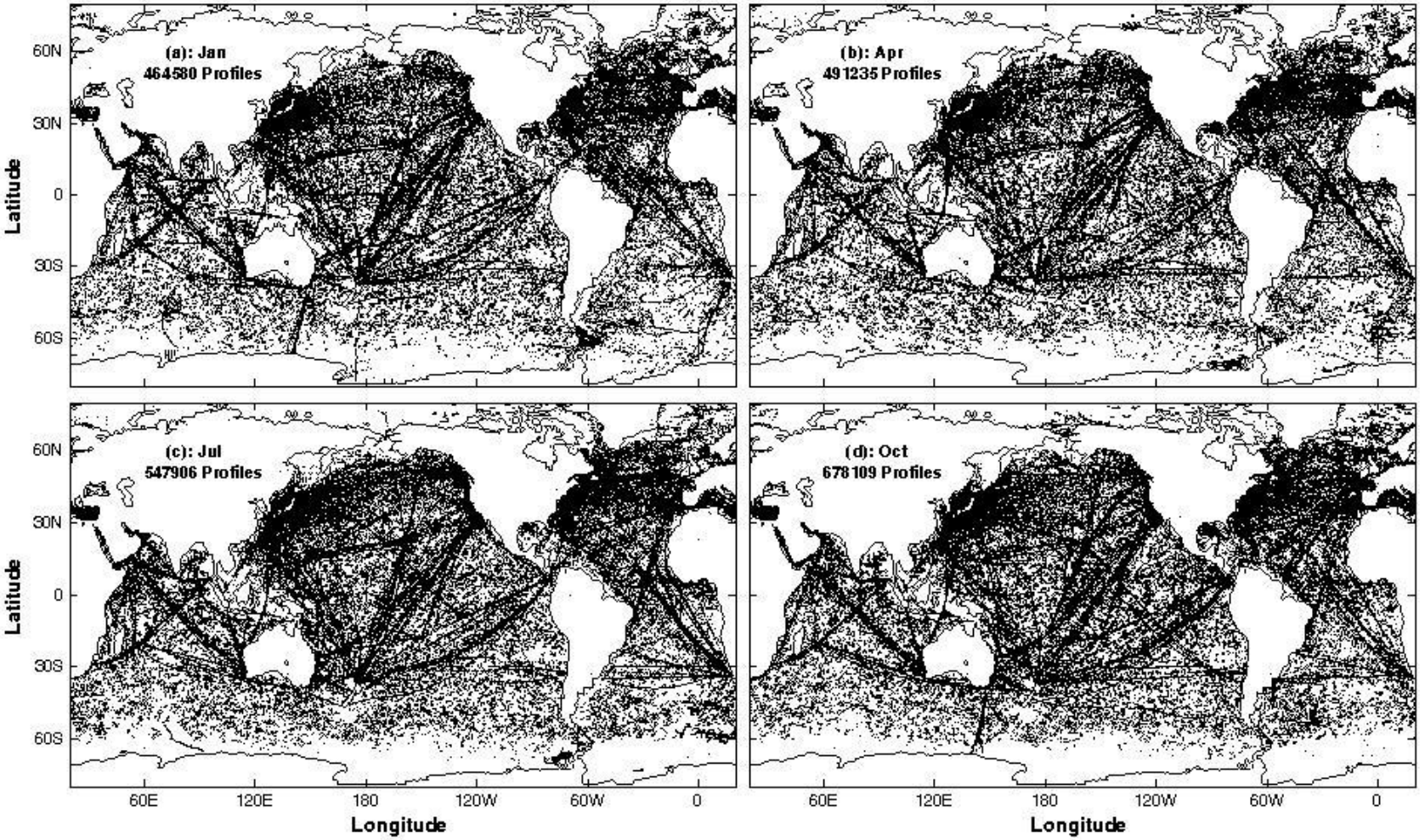
- GTSPP is a joint WMO-IOC program designed to provide improved access to the highest resolution, highest quality data as quickly as possible.
- GTSPP began as an official IODE pilot project in 1989.
- It went into operation in November 1990.



Temporal distribution of GTSPP stations



Spatial distribution of the GTSPP stations



(1) Existing Methods

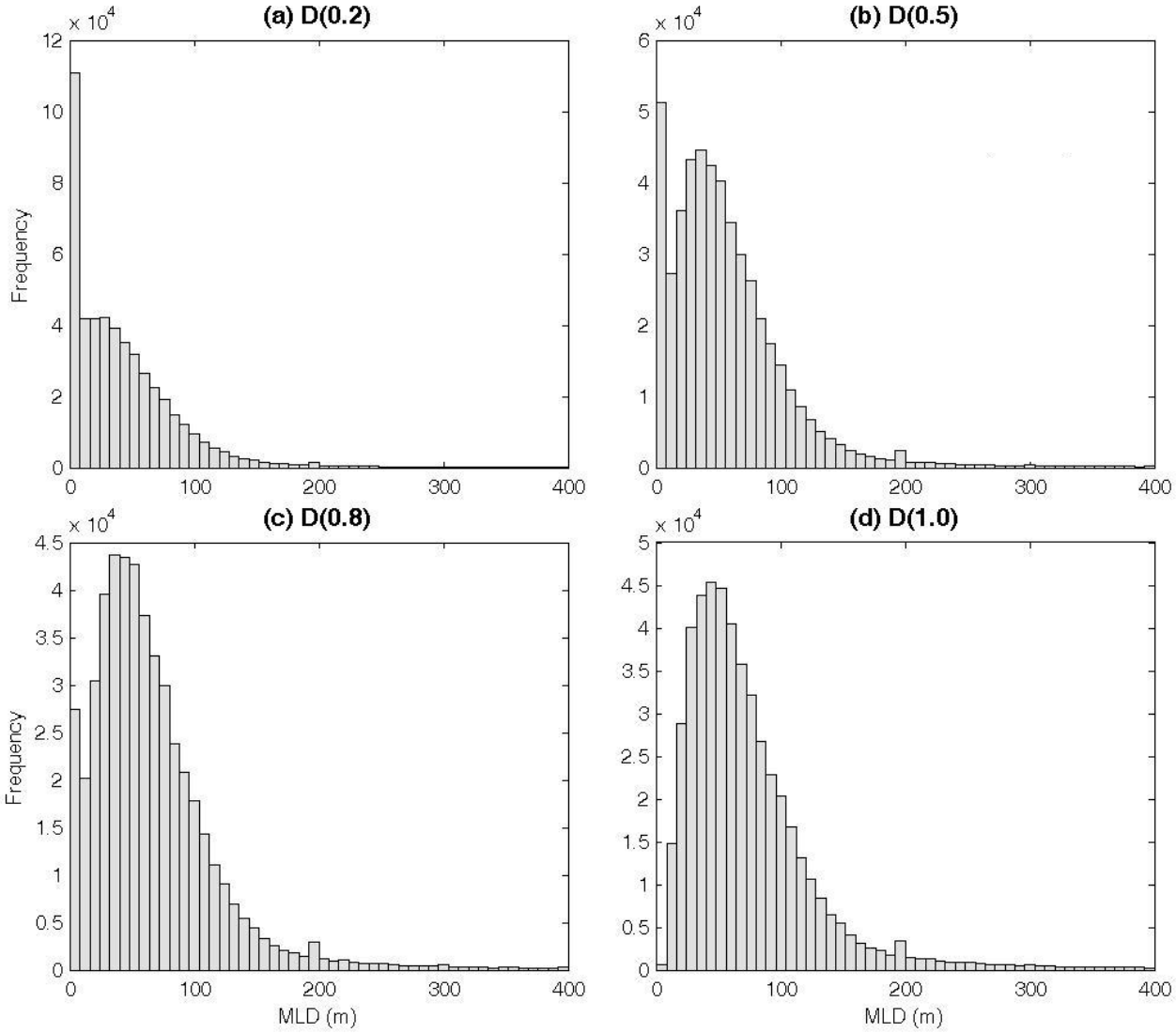
- (a) Difference Method (subjective)
- (b) Gradient Method (subjective)
- (c) Curvature Method (objective but difficult to handle noisy data)

(a) Difference Method

- *T* (or ρ) from its surface value to be smaller than a certain fixed value → H_{mix}

- 0.2°C (Thompson, 1976 North Pacific)
- 0.5°C (Wyrtki 1964; Obata et al., 1996, Global)
- 0.8°C (Kara et al. 2000, Global)
- 1.0°C (Rao et al., 1989, Indian Ocean)

PDF – Global H_{mix} Using 4 Different Criteria



Comparisons

	RMSE(m)	RRMSE
(1,2) :	50.6910	0.8183
(2,3) :	43.3028	0.5651
(3,4) :	70.5309	0.8058
(1,3) :	74.1375	1.0898
(1,4) :	109.2428	1.4917
(2,4) :	88.0147	1.0798

1 → 0.2°C, 2 → 0.5°C, 3 → 0.8°C, 4 → 1.0°C

(b) Gradient Method

- $\partial T/\partial z$ (or $\partial \rho/\partial z$) to be smaller than a certain fixed value → H_{mix}
- 0.015°C/m (Defant, 1961)
- 0.025°C/m (Lukas and Lindstrom, 1991)

(c) Curvature Method

- $\partial^2 T/\partial z^2$ (or $\partial^2 \rho/\partial z^2$) to be maximum at the base of mixed layer
- Chu et al. (1997, 1999, 2000); Lorbacher et al. (2006)
- Objective but difficult to handle noisy data.

$$\left.\frac{\partial^2 T}{\partial z^2}\right|_{z_k} \approx \frac{1}{z_{k+1}-z_{k-1}}\left(\frac{T_{k+1}-T_k}{z_{k+1}-z_k}-\frac{T_k-T_{k-1}}{z_k-z_{k-1}}\right)$$

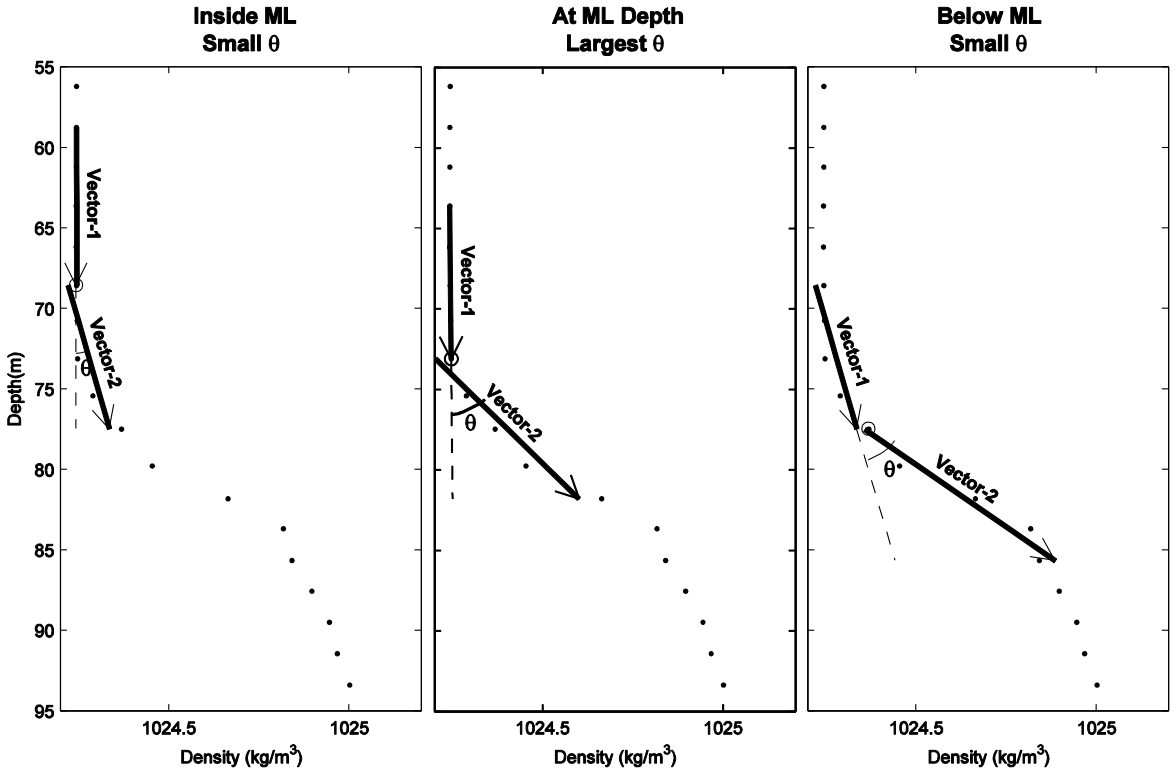
(2) New Method – Maximum Angle

$$\rho(z) = \begin{cases} c_k^{(1)} + G_k^{(1)} z, & z = z_{k-m}, z_{k-m+1}, \cdots z_k \\ c_k^{(2)} + G_k^{(2)} z, & z = z_{k+1}, \cdots z_{k+m} \end{cases}$$

$$\tan\theta_k \rightarrow \max$$

$$H_D = -z_k$$

$$\tan\theta_k = \frac{G_k^{(2)} - G_k^{(1)}}{1 + G_k^{(1)} G_k^{(2)}}$$



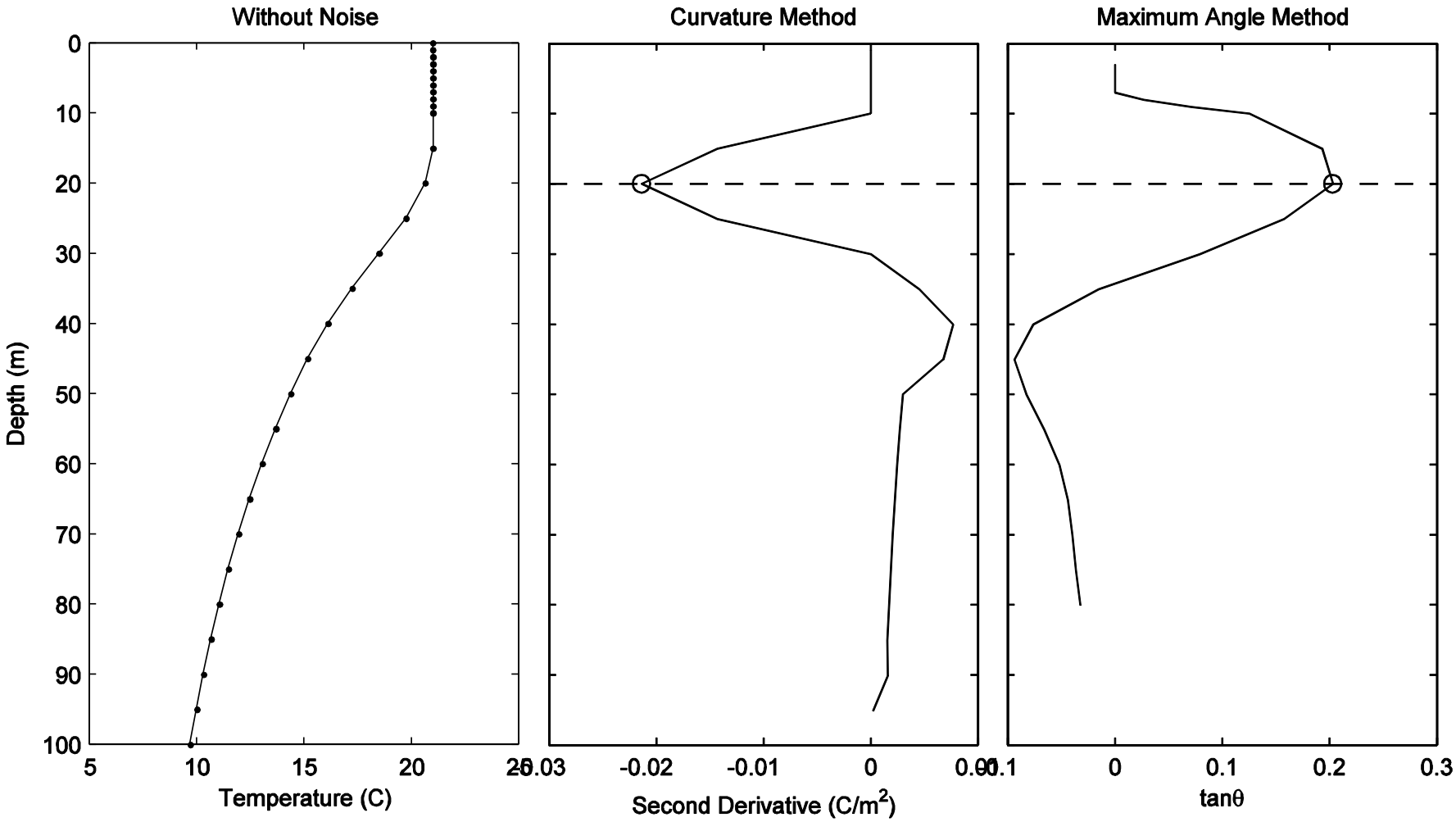
Weakness of the Curvature Method

Use of the analytical profile with 5-point smoothing

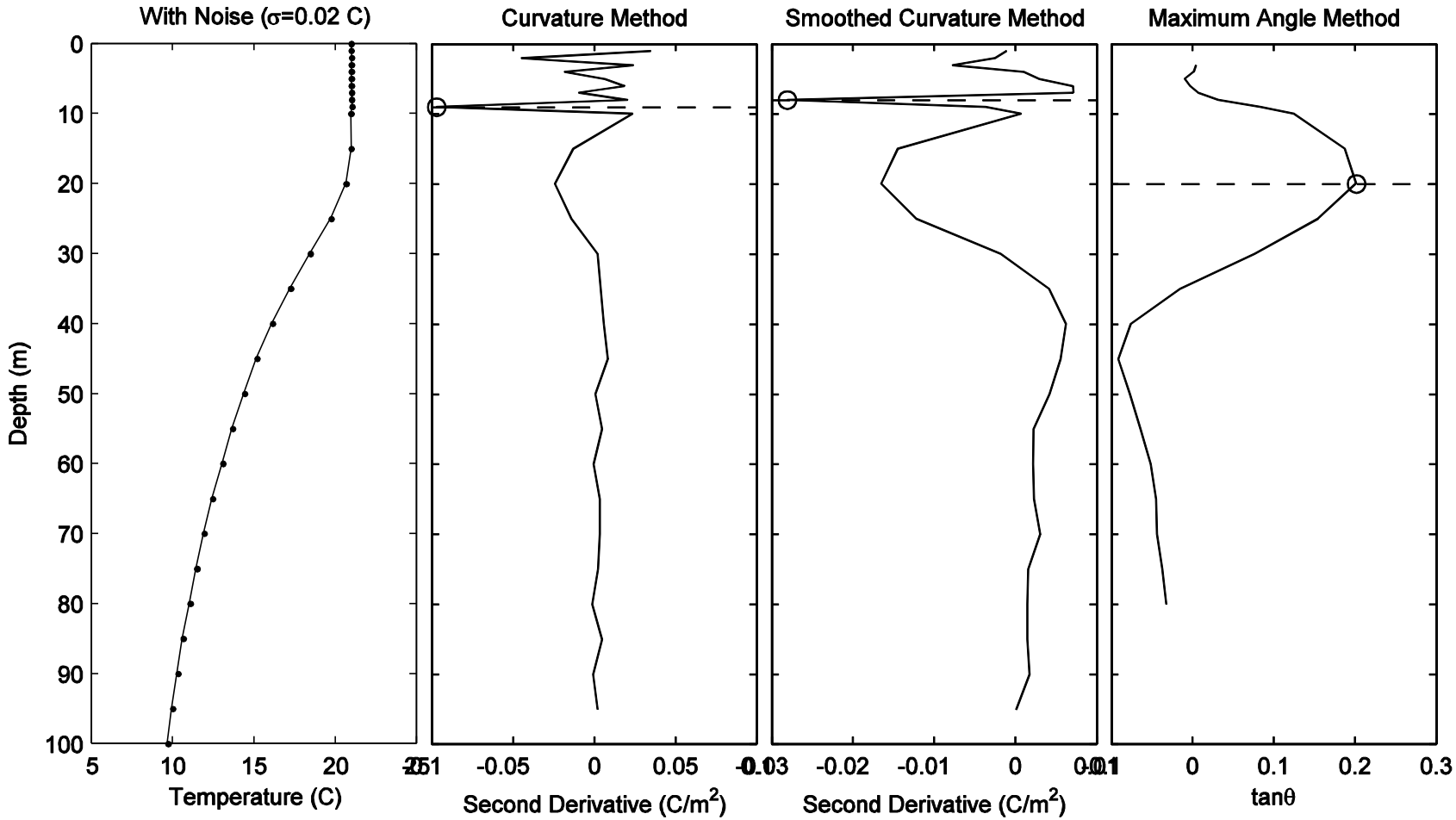
$$T(z) = \begin{cases} 21^{\circ}\mathrm{C}, & -20\ \mathrm{m} < z \le 0\ \mathrm{m} \\ 21^{\circ}C + 0.25^{\circ}C \times (z + 20\ \mathrm{m}), & -40\ \mathrm{m} < z \le -20\ \mathrm{m} \\ 7^{\circ}C + 9^{\circ}C \times \exp\left(\dfrac{z + 40\ \mathrm{m}}{50\ \mathrm{m}}\right), & -100\ \mathrm{m} \le z \le -40\ \mathrm{m}. \end{cases}$$

It is noted that the mixed layer depth is 20 m.

No Noise


Without Noise
Curvature Method
Maximum Angle Method
Depth (m)
0
10
20
30
40
50
60
70
80
90
100
5
10
15
20
25
Temperature (C)
-0.03
-0.02
-0.01
0
0.01
Second Derivative (C/m2)
-0.1
0
0.1
0.2
0.3
tanθ

Profile contaminated by random noise (zero mean and std of 0.02°C) → one realization



Quality Index

Identifying Mixed Layer Depth

Lorbacher et al. (2006)

$$\mathrm{QI} = 1 - \frac{\mathrm{rmsd}\left(T_k - \hat{T}_k\right)\big|_{(H_1, H_D)}}{\mathrm{rmsd}\left(T_k - \hat{T}_k\right)\big|_{(H_1, 1.5\times H_D)}}$$

QI = 1 → highest quality

QI > 0.8 → mixed layer depth well defined

0.8 > QI > 0.5 → mixed layer depth determined with uncertainty

QI< 0.5 → mixed layer depth cannot be determined

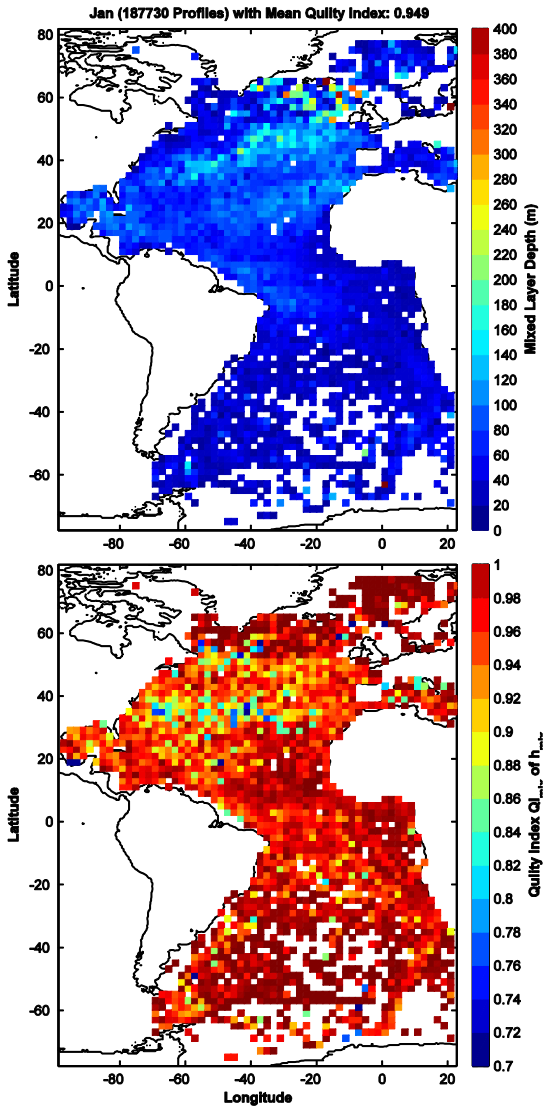
(3) Global Ocean Mixed Layer Data

from Global Temperature and Salinity Profile Program (GTSPP)

Mixed Layer Depth (density)

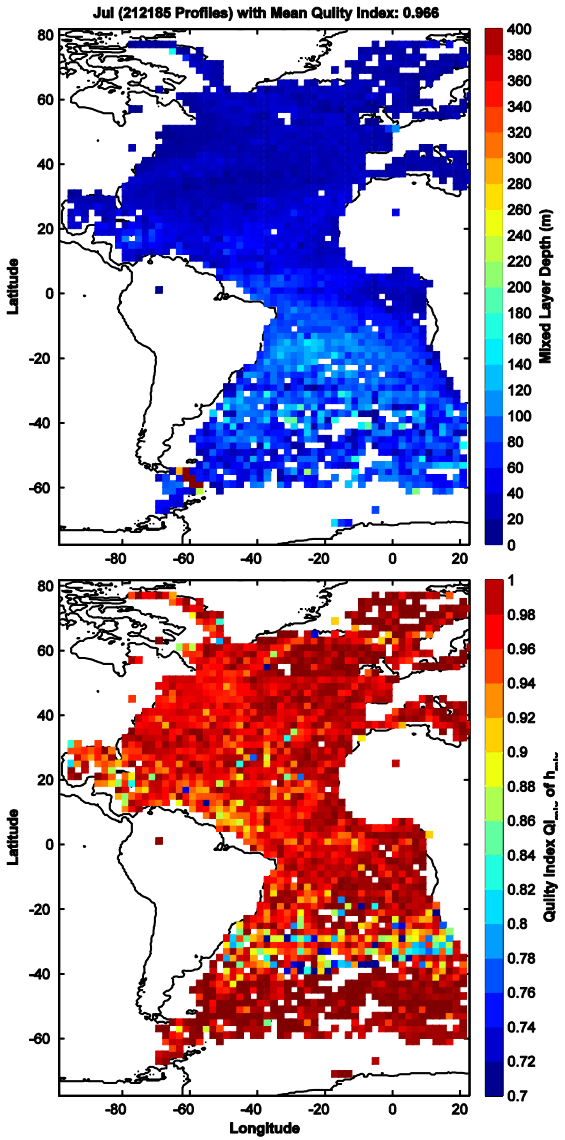
January

QI = 0.960



July

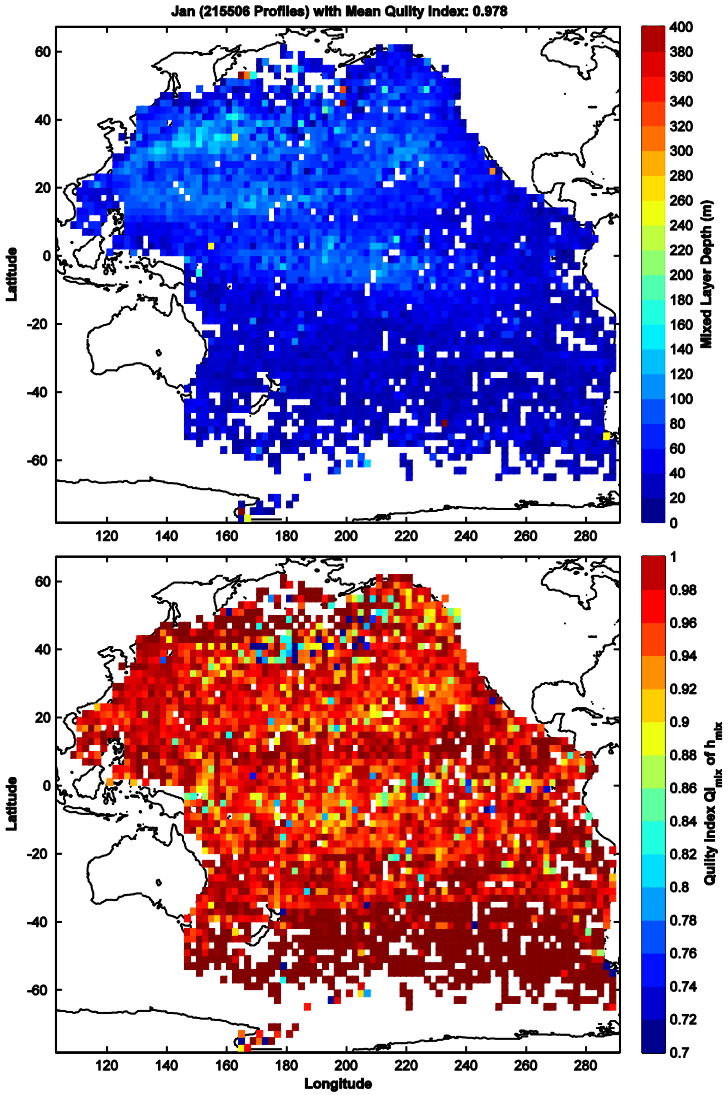
0.968



Mixed Layer Depth (density)

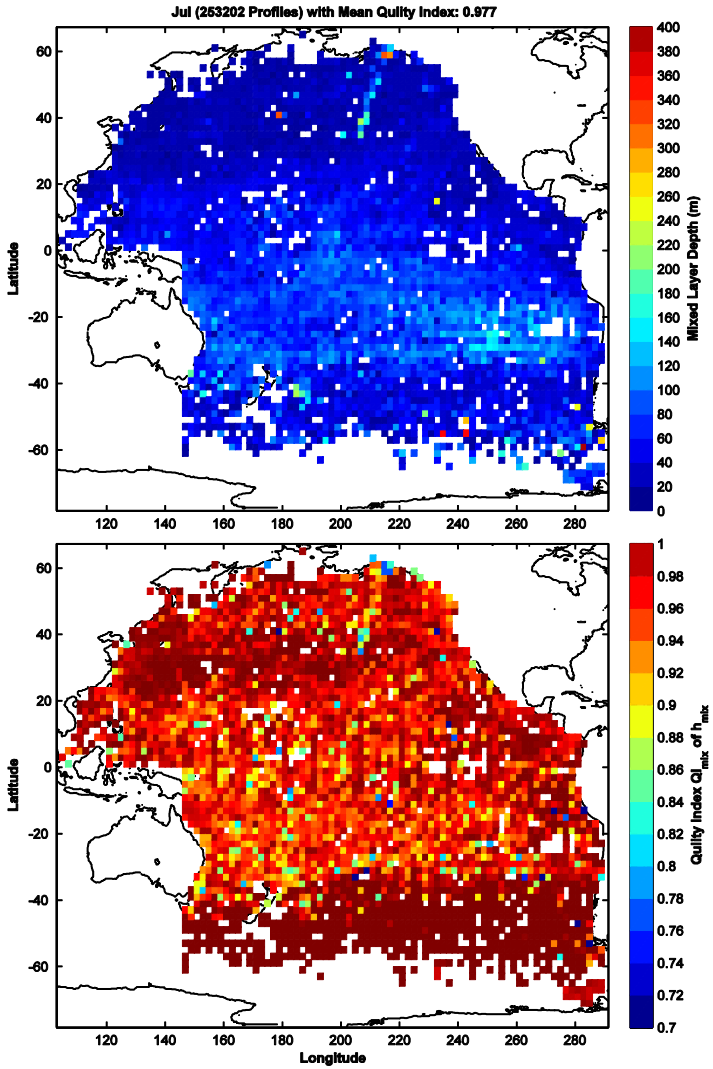
January

QI = 0.971



July

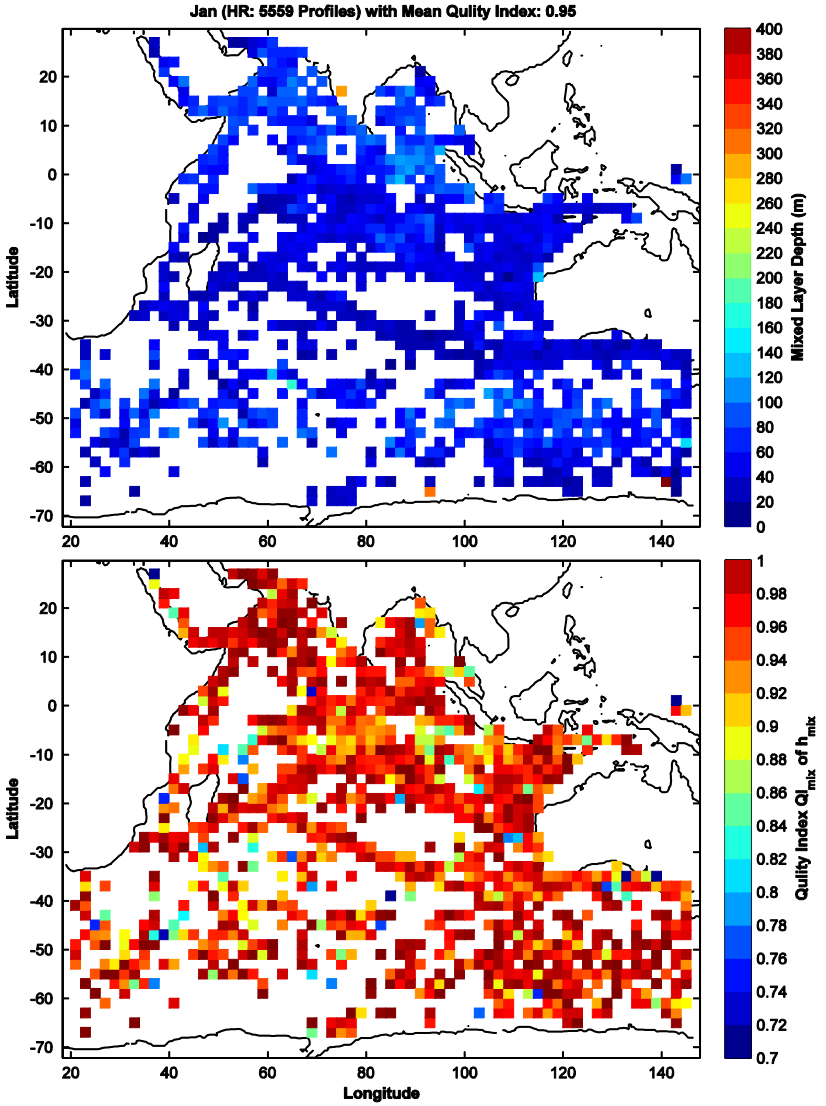
QI = 0.963



Mixed Layer Depth (density)

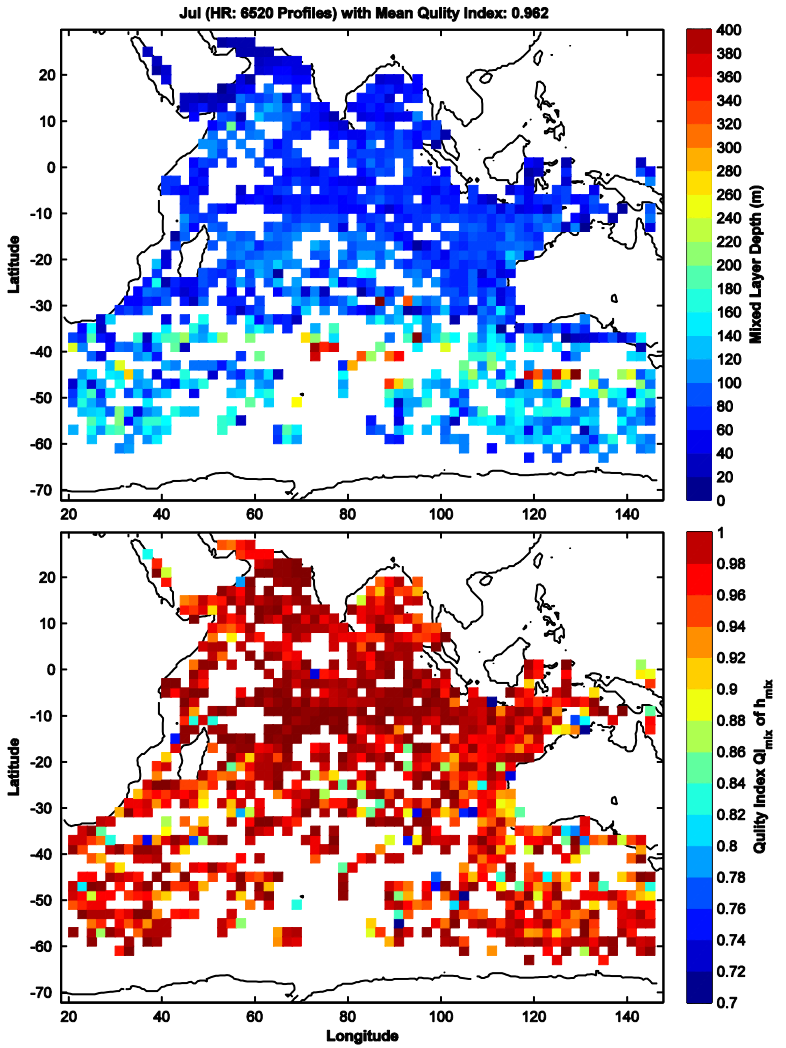
January

QI= 0.974



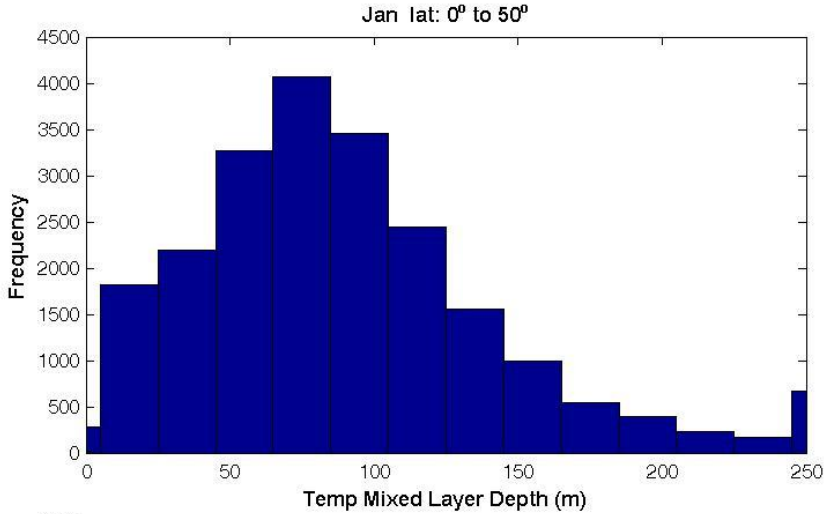
July

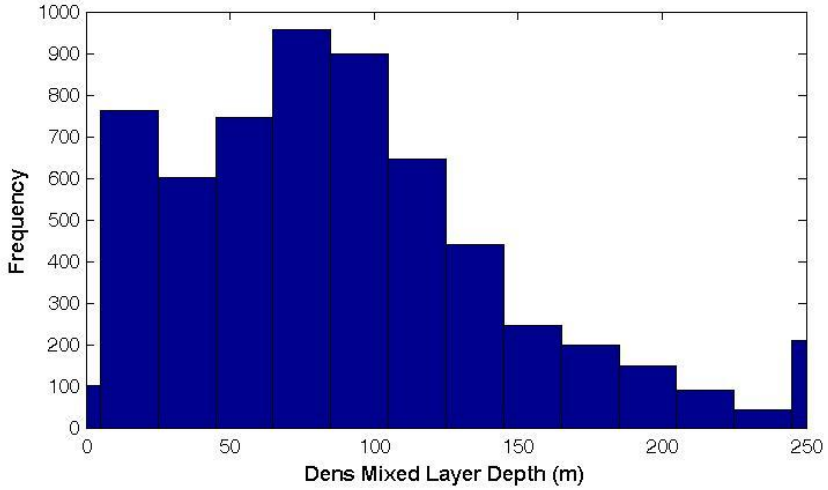
QI = 0.977



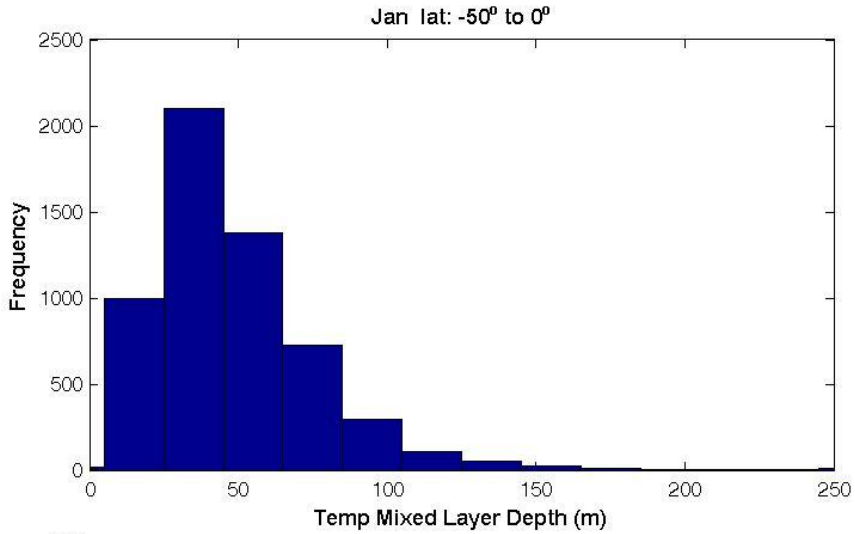
Atlantic Ocean (January)

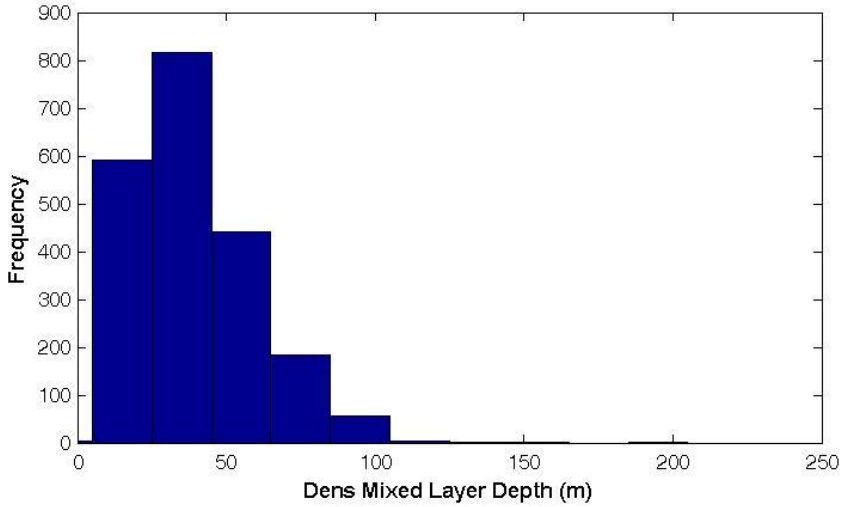
Northern





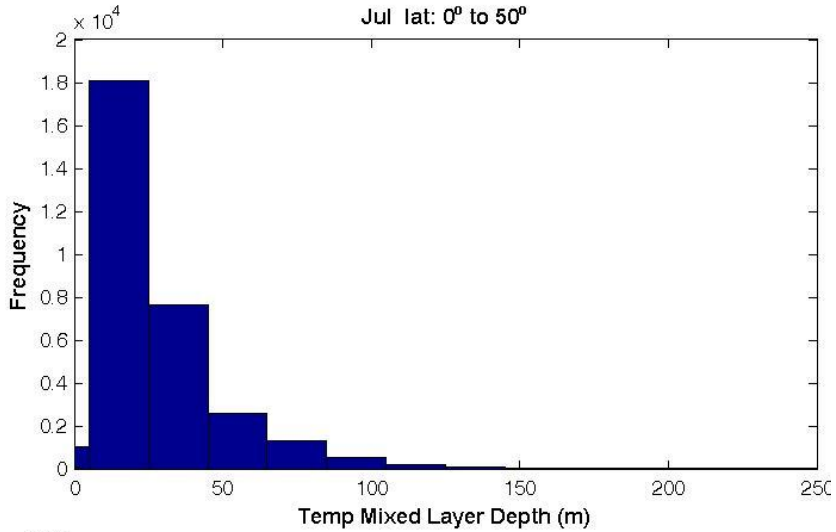
Southern

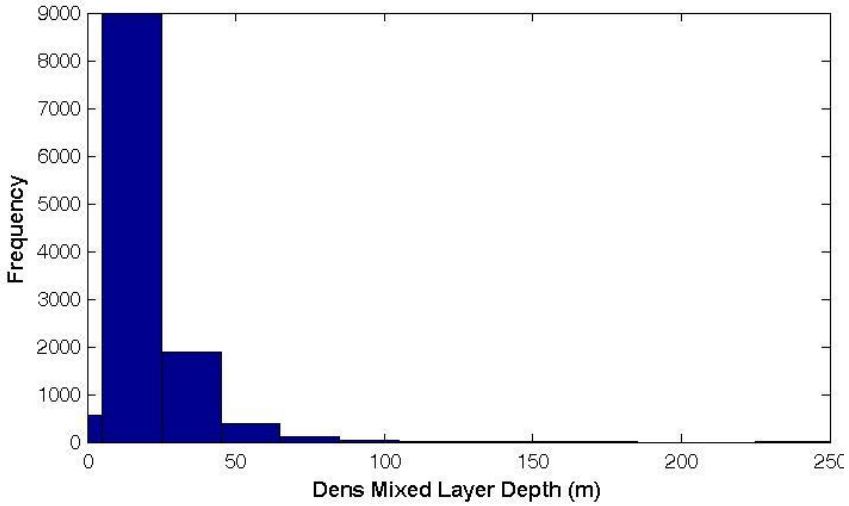




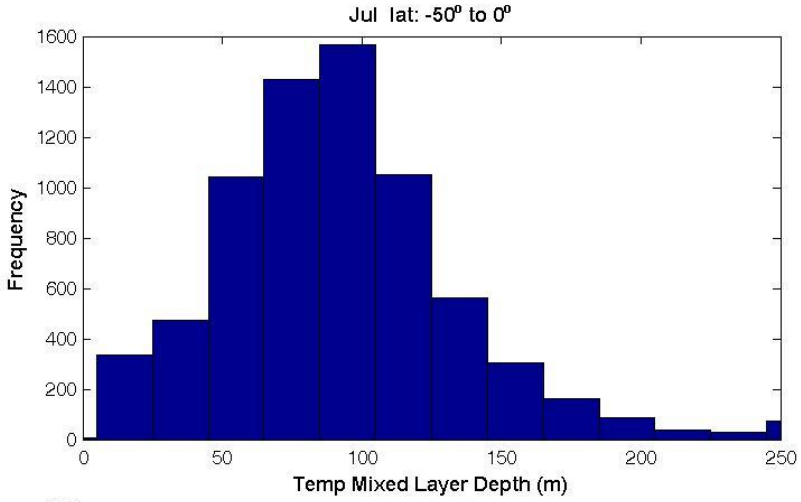
Atlantic Ocean (July)

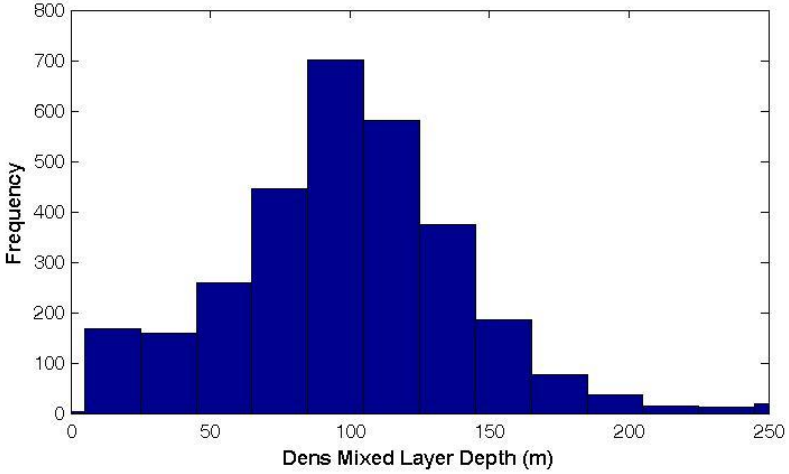
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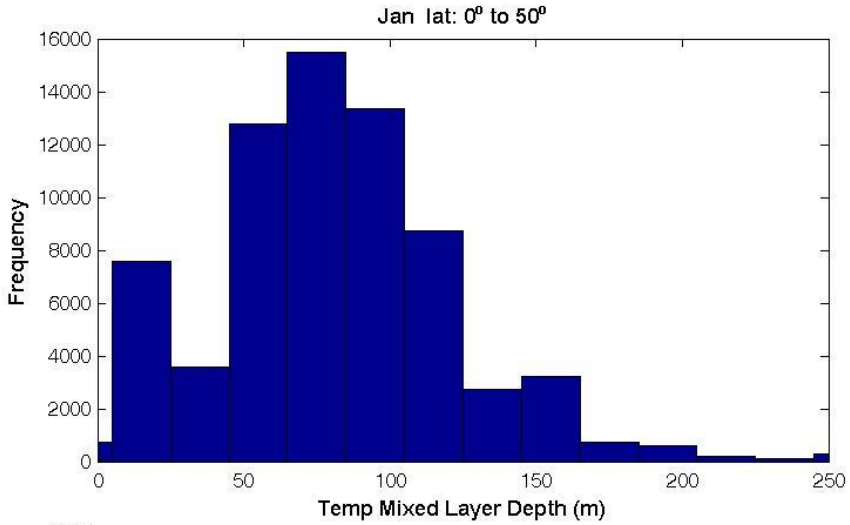
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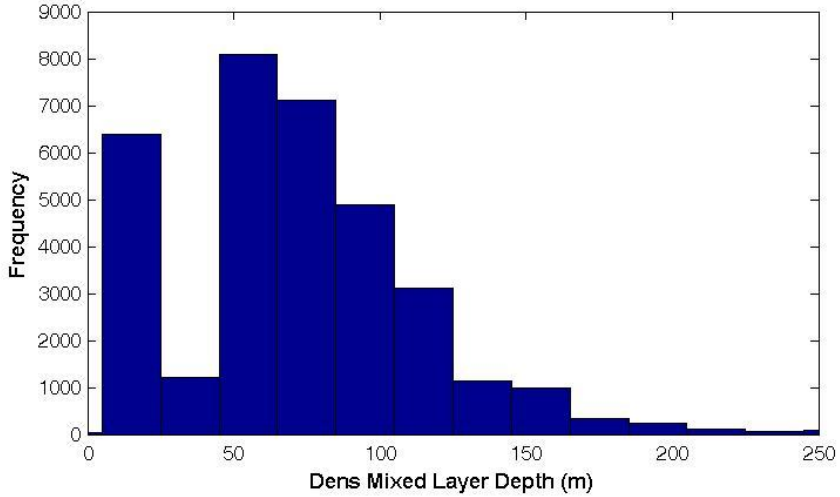




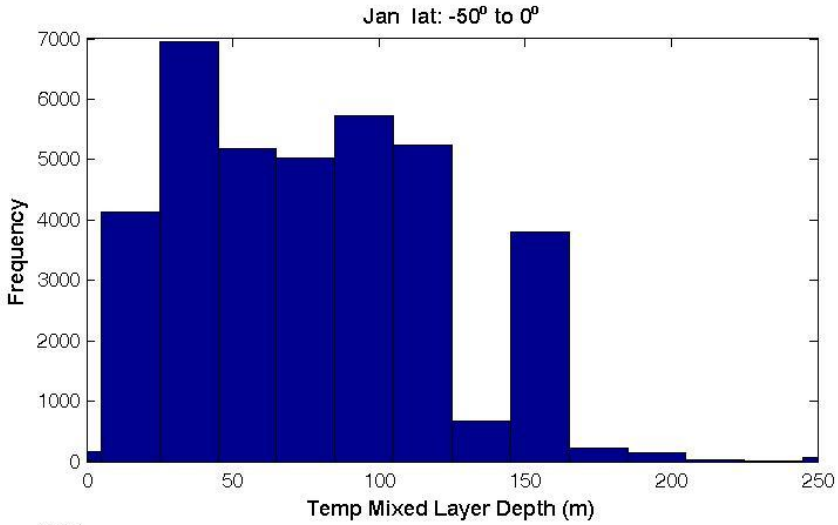
Pacific Ocean (January)

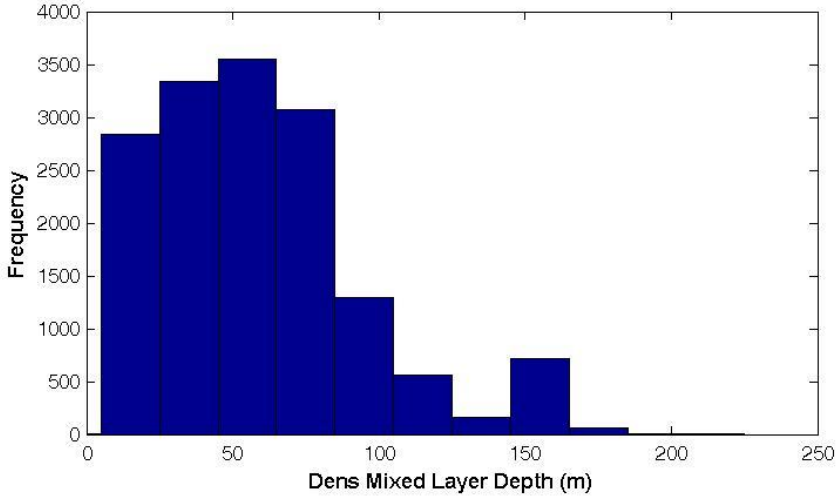
Northern





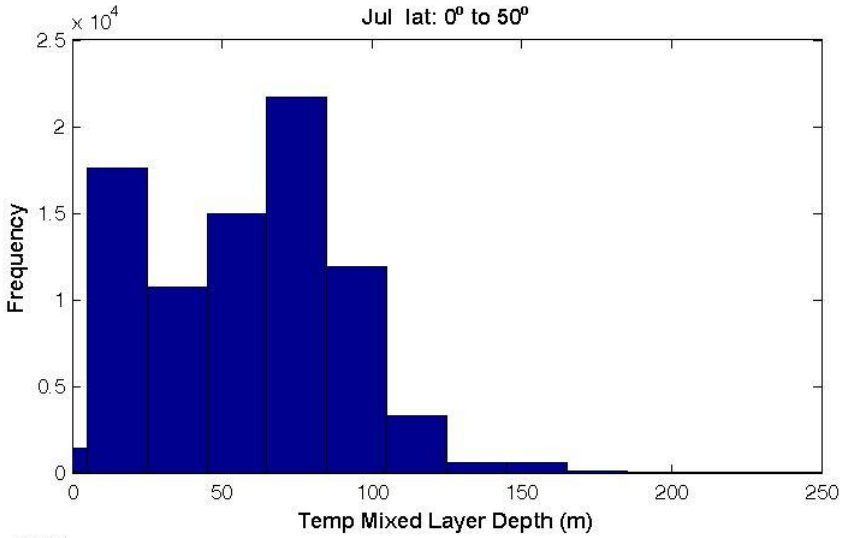
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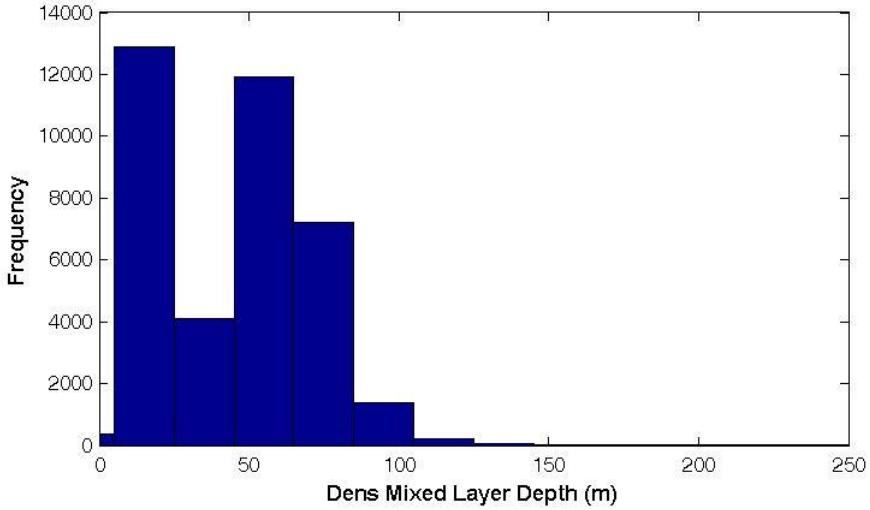




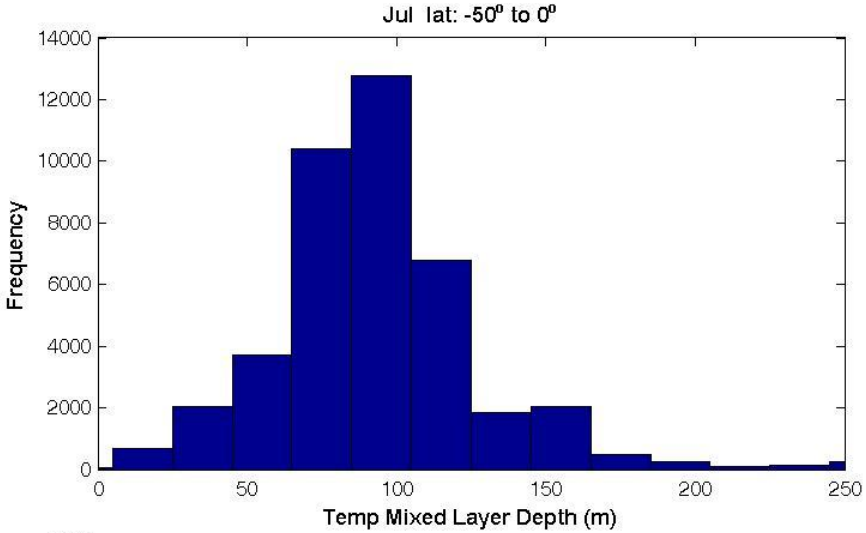
Pacific Ocean (July)

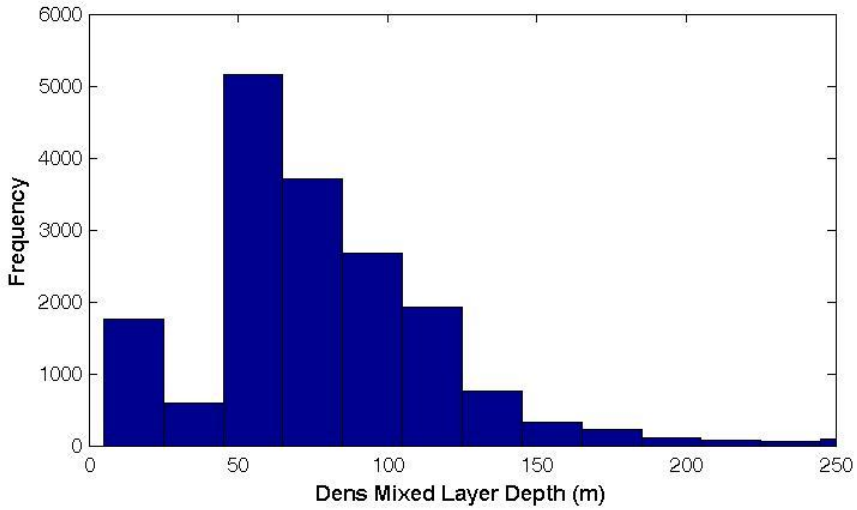
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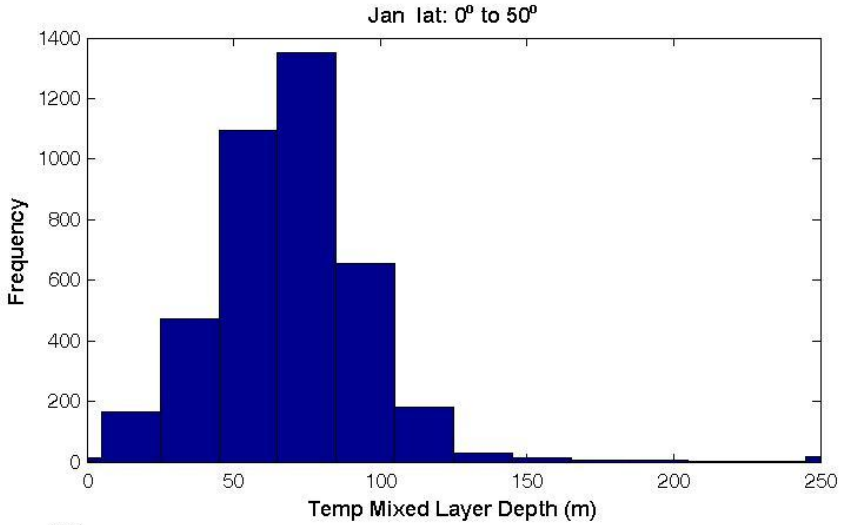
Southern

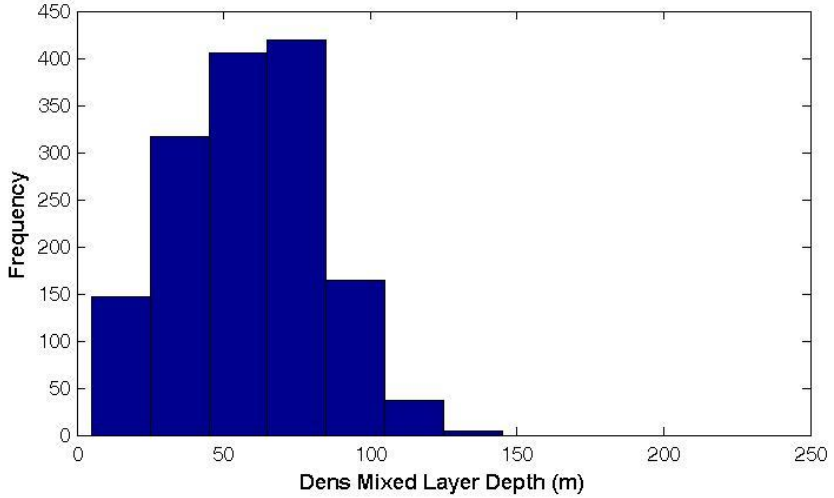




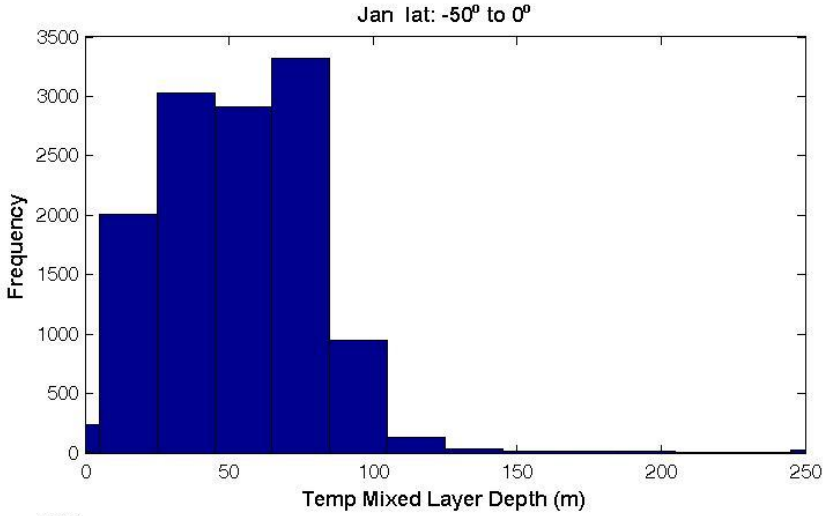
Indian Ocean (January)

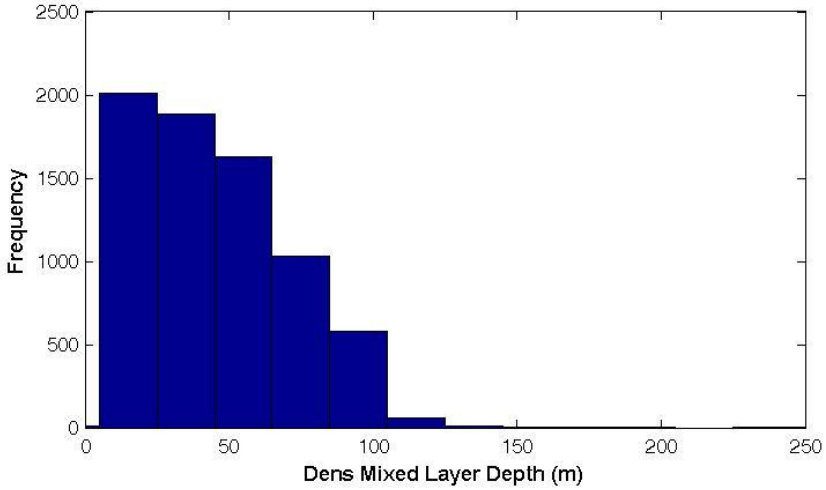
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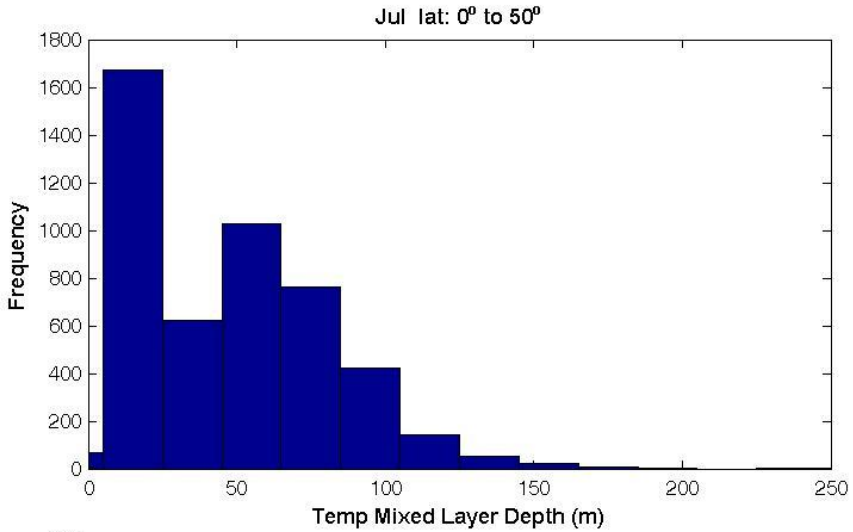
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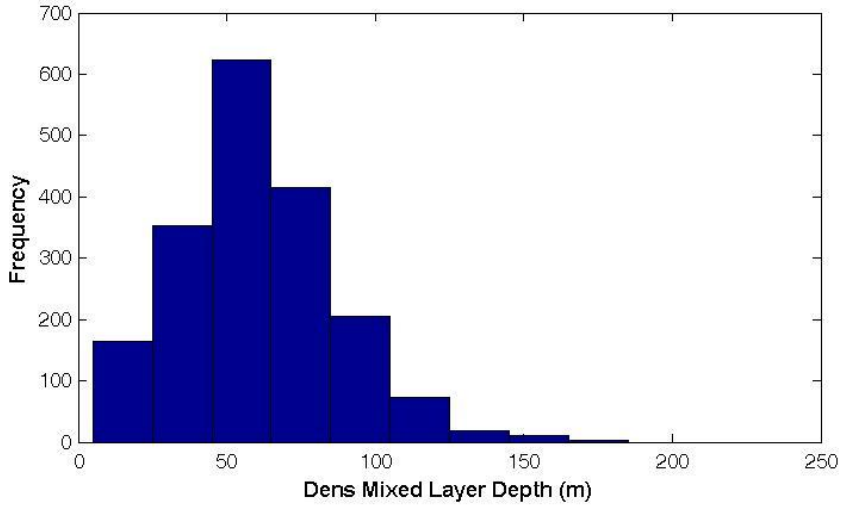




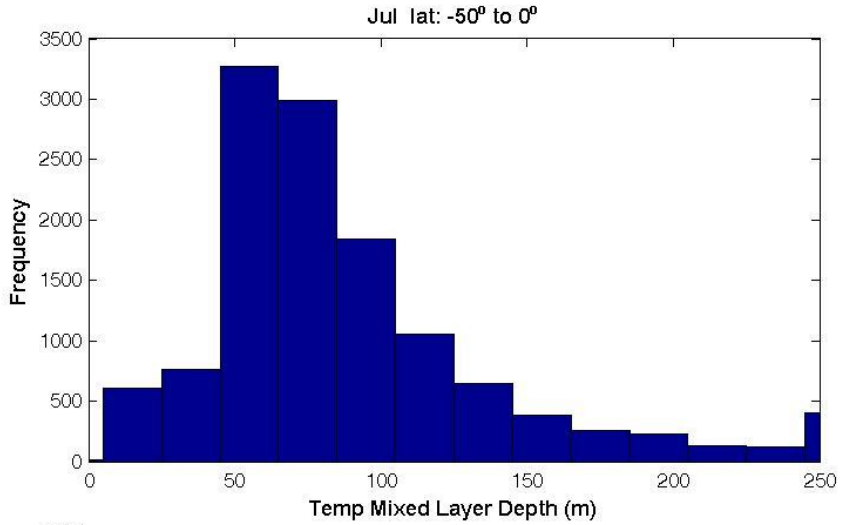
Indian Ocean (July)

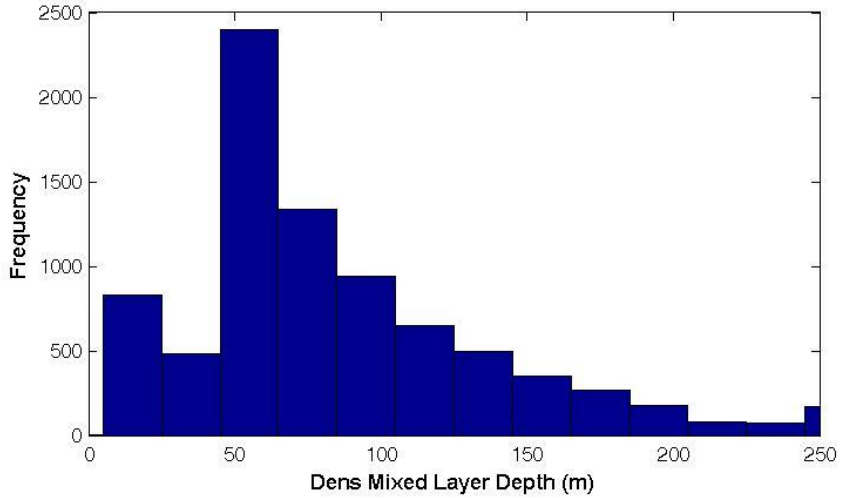
Northern





Southern





Conclusions

- (a) The maximum angle method is totally objective without any initial guess (no iteration).
- (b) This method can handle noisy data since no any differentiations (first or second) are calculated for the profile data.
- (c) The calculated (H_D, H_T) are ready to use for various studies.