Defining the Transition Layer Based on Ocean Mooring Data

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1. Introduction

An important role in climate is played by the surface mixed layer, the upper ocean layer well mixed in ocean properties. Wind stress forcing causes a spiraling Ekman flow in the rotating ocean that decays with depth and transports momentum into the ocean. Conventional viewpoint suggests that the wind-driven flow does not penetrate deeper than the mixed layer, but observations show the wind-driven momentum and shear penetrate deeper into the transition layer [1], the region where mixing rates transit from high values in the mixed layer to low values in the interior. This deeper momentum transfer into the poorly understood transition layer has significant effects on ocean dynamics.

In this study, transition layer is researched by using pre-existing mooring data (from D. Rudnick, Scrippts Institution of Oceanography and Upper Ocean Process Data Archives, Woods Hole Oceanographic Institute), which includes surface flux, current, temperature and salinity data at multiple geographic locations in different dynamical regimes. Wind stress penetration depth, mixed layer depth, shear and stratification time series are calculated. Previous research by Plueddemann and Weller [2] and Rudnick [3] shows the mixed layer has low shear, while the transition layer is an area of high shear. The transition layer also transits from the non-stratified mixed layer to the highly stratified interior and hence should be a region with high stratification.

The transition layer thickness is calculated in several ways in this study: the depth difference between Ekman depth and mixed layer depth, layer thickness below the mixed layer with high shear, and layer thickness below the mixed layer with high stratification. These various definitions of transition layer are compared to derive a more comprehensive definition of the transition layer depth and to provide characterization of this layer in three different geographic regions. The transition layer characteristics from moored data are compared to the results of the characteristics of transition layer derived from SeaSoar data as analyzed by Johnston and Rudnick in 2007 [4].

2. Data Sets

Data from three geographically different regions is used for the analysis. The first mooring is located in the Arabian Sea (Arabian) at 15.725°N, 61.267°E and spans November 1994 to

April 1995 (data provided by D. Rudnick) [5]. The second mooring is in the western tropical Pacific warm pool located at 1.755°S, 155.994°E and was collected for the Tropical Ocean - Global Atmosphere Coupled Ocean - Atmosphere Response Experiment (TOGA COARE) [6] and spans October 21, 1992 to March 4, 1993 (data provided by Upper Ocean Process Data Archives, Woods Hole Oceanographic Institute). The last mooring is in the sub-Arctic North Atlantic ocean located at 59.593°N, 20.965°W for the Marine Light - Mixed Layer Experiment (MLML) [7] and spans April, 29 1991 to September 6, 1991 (data provided by Upper Ocean Process Data Archives, Woods Hole Oceanographic Institute).

3. Methods

Temperature, salinity, velocity and wind stress data are put into hourly blocks. For large sections where salinity is unknown, the missing values are obtained using linear interpolation. Temperature, salinity and velocity data are interpolated to the same depths. For the Arabian Sea mooring the data are interpolated to every four meters, which is the measured resolution for velocity. TOGA COARE and MLML mooring data are interpolated every eight meters. The data are then averaged using a seven day running mean to remove the diurnal cycle. The mixed layer depth is taken to be the depth where the temperature changes by 0.1°C. The Ekman depth is calculated for each mooring by integrating the velocity to the depth that best matches the theoretical Ekman transport.

The transition layer thickness is defined by five different definitions: Ekman thickness, N^2_{fwhm} thickness, N^2_{max} thickness, shear^2_{fwhm} thickness, shear^2_{max} thickness. The Ekman thickness is defined as the thickness from mixed layer depth to the Ekman transport depth. The acronym fwhm stands for full width at half max and is defined as half of the maximum and a background value taken to be the mean. The top extent of the fwhm thickness is the depth above the maximum whose value is half of the sum of the maximum and the mean. If the values above the maximum exceed the mean, then the shallowest depth is used. The bottom extent of this thickness is the depth below the maximum whose value is half of the sum of the maximum and mean. The max thicknesses are defined as thickness from the mixed layer depth to the depths of the max that occur below the mixed layer.

4. Results

The Ekman transport depth (wind stress penetration depth) calculation is done for all three moorings; although there is not perfect agreement with theory, the normalization of the measured value to the calculated value oscillates about the value of one and the angle oscillates about zero degrees. The oscillation are as much above as below the expected value, therefore the measured Ekman depth is taken to be correct and agree well with theory. The plots for the Arabian sea mooring, TOGA COARE mooring and MLML mooring are shown in Figure 1, Figure 2 and Figure 3, respectively.

The five different methods for measuring the transition layer thickness are plotted for the Arabian Sea mooring in Figure 4, for the TOGA COARE mooring in Figure 5, and for the MLML mooring in Figure 6. For parts of Arabian Sea data, there are periods where stratification stays above the mean and the bottom extent of N^2_{fwhm} cannot be calculated.

The mean, standard deviation and median of transition layer thickness across the entire time series for each of the five different definitions are shown in Table 1. The values of the mean and median are in mutual agreement for several of the transition layer thickness definitions. Future work will include intercomparison of these definitions by using functional linear regressions.

5. Discussion

Five different definitions of transition layer and transition layer thickness have been defined. For the Arabian Sea mooring and the TOGA COARE mooring, the mean of the max defined thicknesses are deeper than the mean of the fwhm defined thicknesses. The opposite is true for the MLML mooring. The mean and median values found here are comparable to the recent results from Johnston and Rudnick [4] using SeaSoar data, but show a larger variability.

Acknowledgements. This work could not have been completed without the help of Daniel Rudnick and Shaun Johnston of Scripps Institution of Oceanography and the help of Robert Weller and Albert Plueddemann of the Woods Hole Oceanographic Institution. This material is based upon work supported by the National Science Foundation under Grant No. OCE-0612154 and OCE-0623264. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the author(s) and do not necessarily reflect the views of the National Science Foundation.

	Mean	Standard Deviation	Median
Arabian Sea			
N^2_{fwhm}	21.6	8.4	19.6
N^2_{max}	55.4	44.7	26.0
$shear^2_{fwhm}$	15.4	23.7	8.1
$shear^2_{max}$	41.0	37.6	26.5
Ekman	26.4	29.0	20.3
TOGA COARE			
N^2_{fwhm}	35.9	18.7	30.7
N^2_{max}	69.6	26.4	77.0
$shear^2_{fwhm}$	39.3	30.9	28.4
$shear^2_{max}$	68.6	45.5	74.4
Ekman	56.9	50.7	37.3
MLML			
N^2_{fwhm}	31.9	12.4	30.5
N^2_{max}	10.1	12.6	5.5
$shear^2_{fwhm}$	24.1	19.8	9.8
$shear^2_{max}$	51.0	25.7	67.6
Ekman	17.0	24.5	15.5

Table 1: Mean, standard deviation and median transition layer thickness, including mean standard deviation for the five different transition layer thickness for each mooring. All values are in meters.

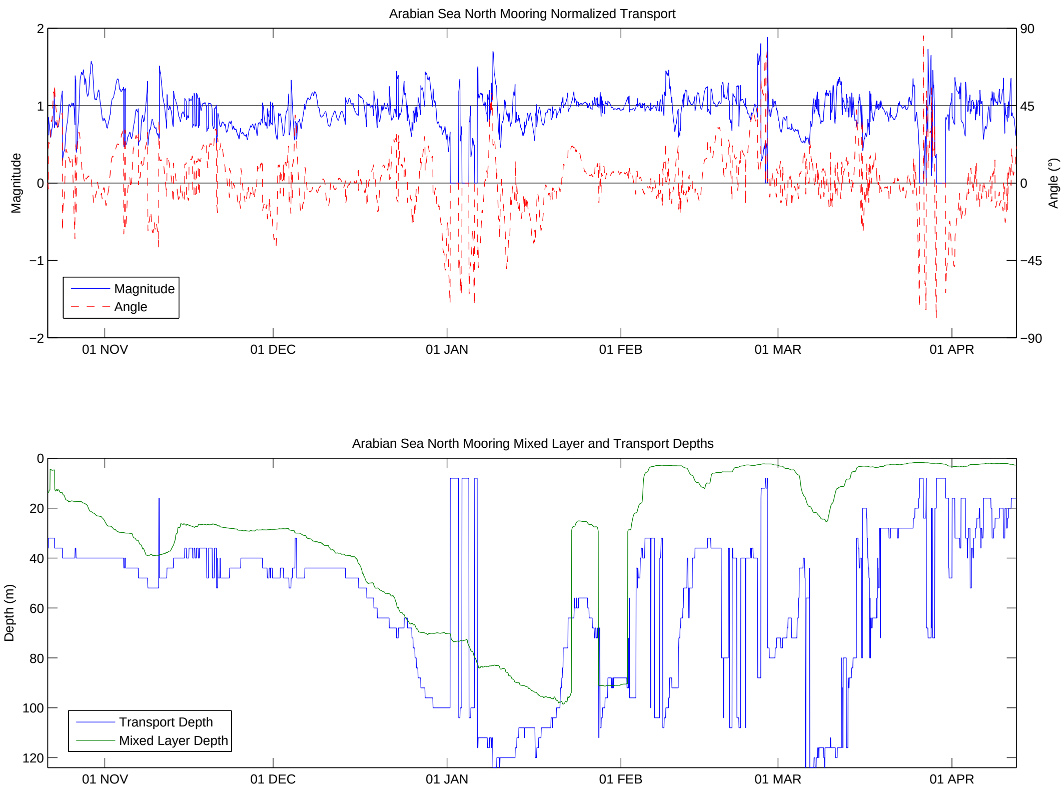

Figure 1: Arabian Sea Mooring Mixed Layer Depth and Ekman Depth during November 1994 through April 1995. The top plot shows the magnitude (blue curve) and angle (dashed red curve) of the observed transport normalized by the theoretical Ekman transport. Perfect agreement with theory would produce a magnitude of one and an angle of zero degrees. The bottom plot shows the mixed-layer depth (green curve) and the observed Ekman layer depth (blue curve).

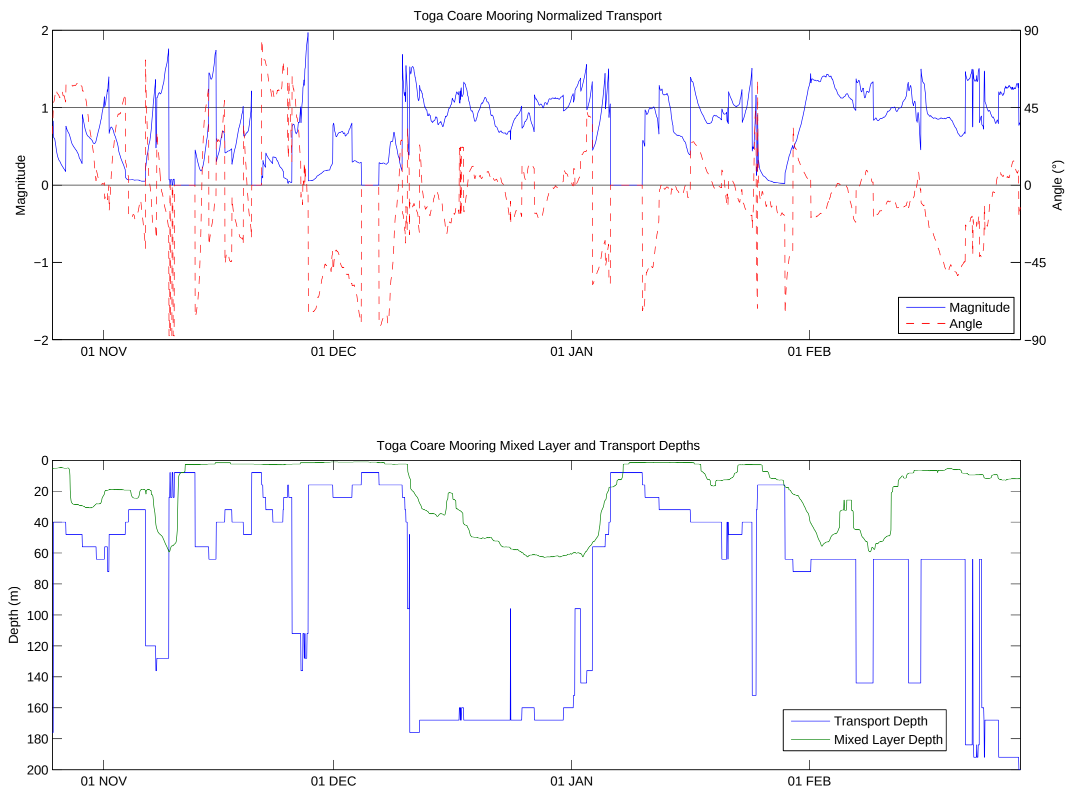

Figure 2: TOGA COARE Mooring Mixed Layer Depth and Ekman Depth during October 1992 through March 1993. The top plot shows the magnitude (blue curve) and angle (dashed red curve) of the observed transport normalized by the theoretical Ekman transport. Perfect agreement with theory would produce a magnitude of one and an angle of zero degrees. The bottom plot shows the mixed-layer depth (green curve) and the observed Ekman layer depth (blue curve).

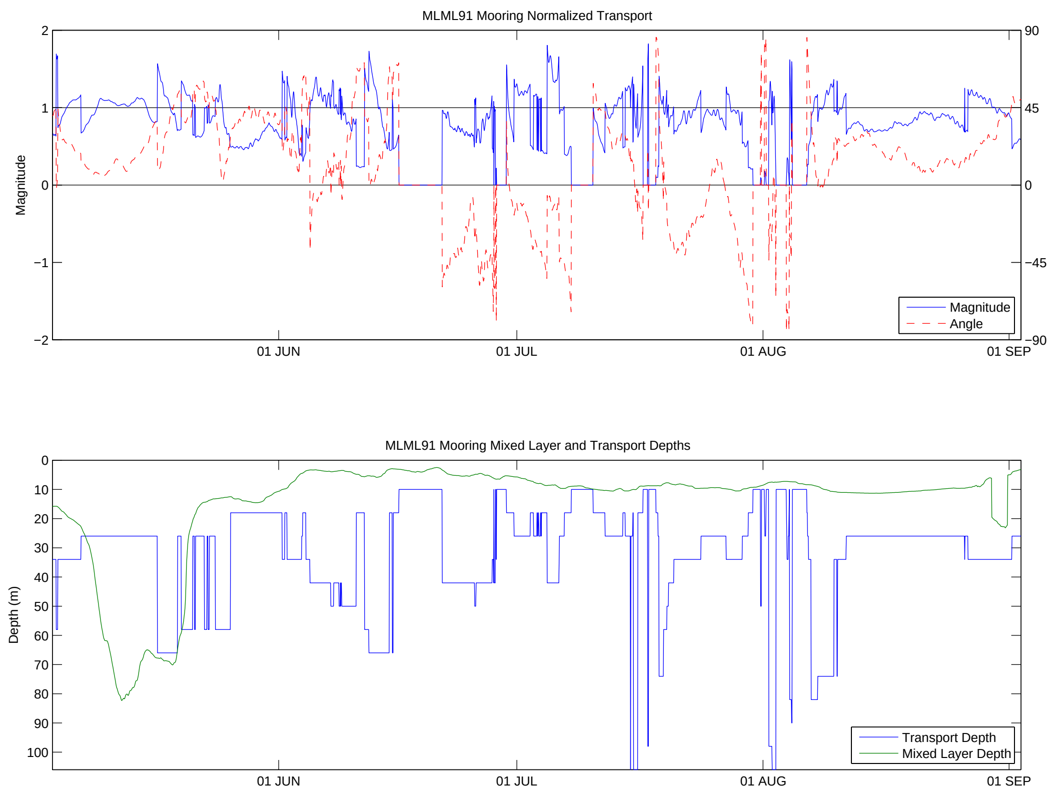

Figure 3: MLML Mooring Mixed Layer Depth and Ekman Depth during April 1991 through September 1991. The top plot shows the magnitude (blue curve) and angle (dashed red curve) of the observed transport normalized by the theoretical Ekman transport. Perfect agreement with theory would produce a magnitude of one and an angle of zero degrees. The bottom plot shows the mixed-layer depth (green curve) and the observed Ekman layer depth (blue curve).

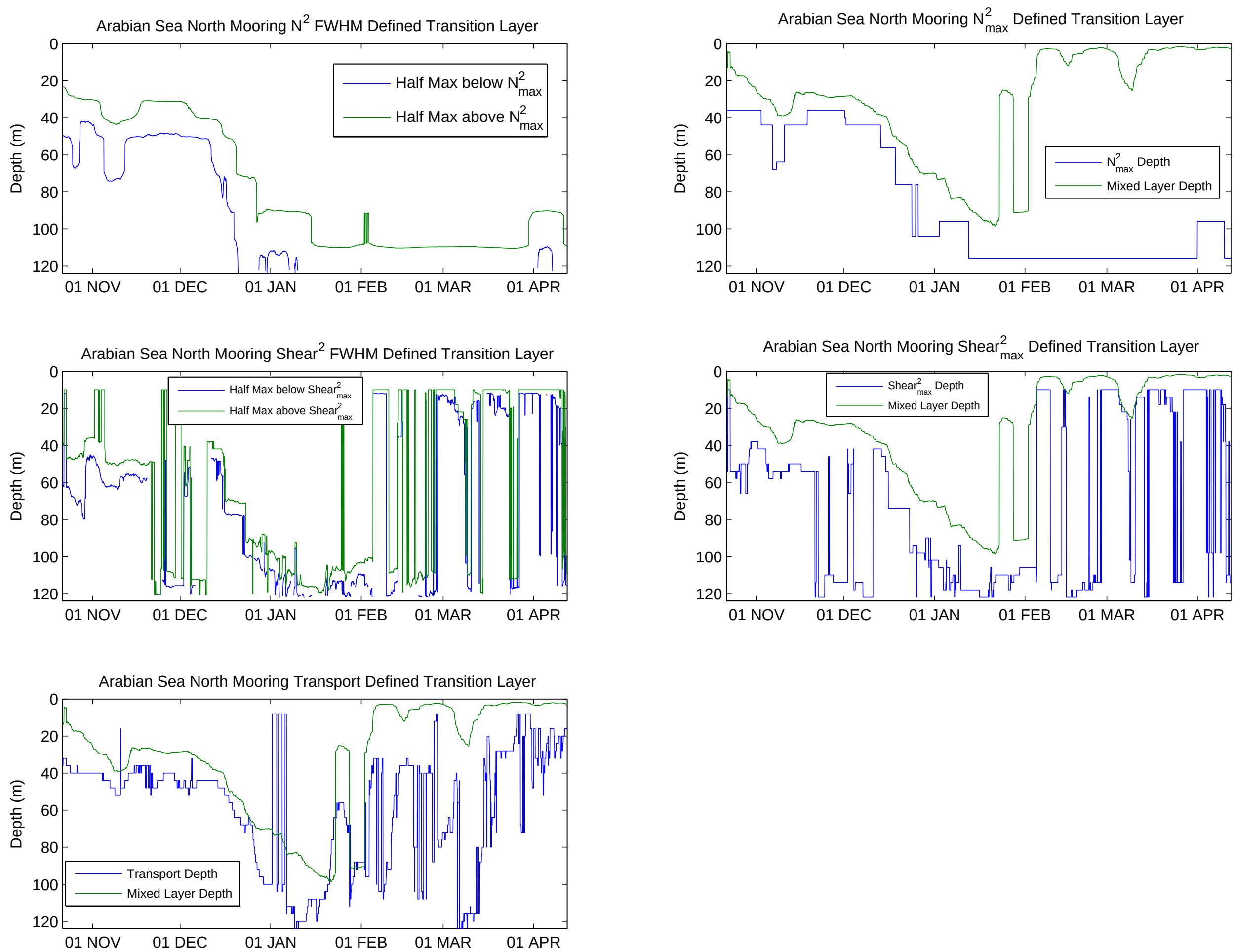

Figure 4: Arabian Sea Mooring Transition Layer Thicknesses during November 1994 through April 1995. In each plot, the transition layer is the region between the two curves, with the green curve defining the top of the transition layer and the blue curve defining the bottom of the transition layer. The top left plot shows transition layer defined by N^2_{fwhm}; the top right defined by N^2_{max}; the middle left defined by $shear^2_{fwhm}$; the middle right defined by $shear^2_{max}$; the bottom left defined by the Ekman depth. Note that when the Ekman transport depth is shallower than the mixed layer depth the Ekman thickness definition cannot be used to define the transition layer.

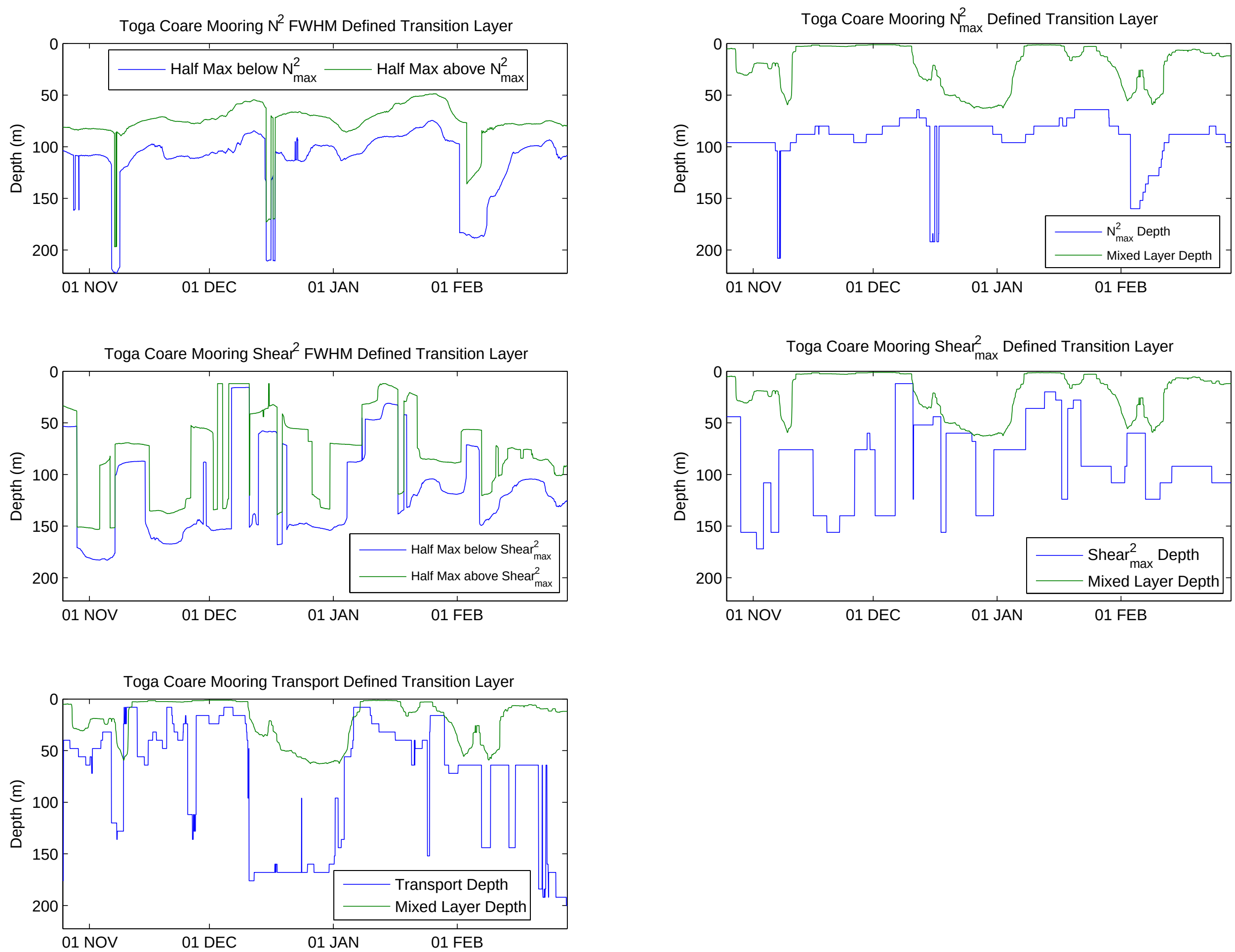

Figure 5: TOGA COARE Mooring Transition Layer Thicknesses during October 1992 through March 1993. In each plot, the transition layer is the region between the two curves, with the green curve defining the top of the transition layer and the blue curve defining the bottom of the transition layer. The top left plot shows transition layer defined by N^2_{fwhm}; the top right defined by N^2_{max}; the middle left defined by $shear^2_{fwhm}$; the middle right defined by $shear^2_{max}$; the bottom left defined by the Ekman depth. Note that when the Ekman transport depth is shallower than the mixed layer depth the Ekman thickness definition cannot be used to define the transition layer.

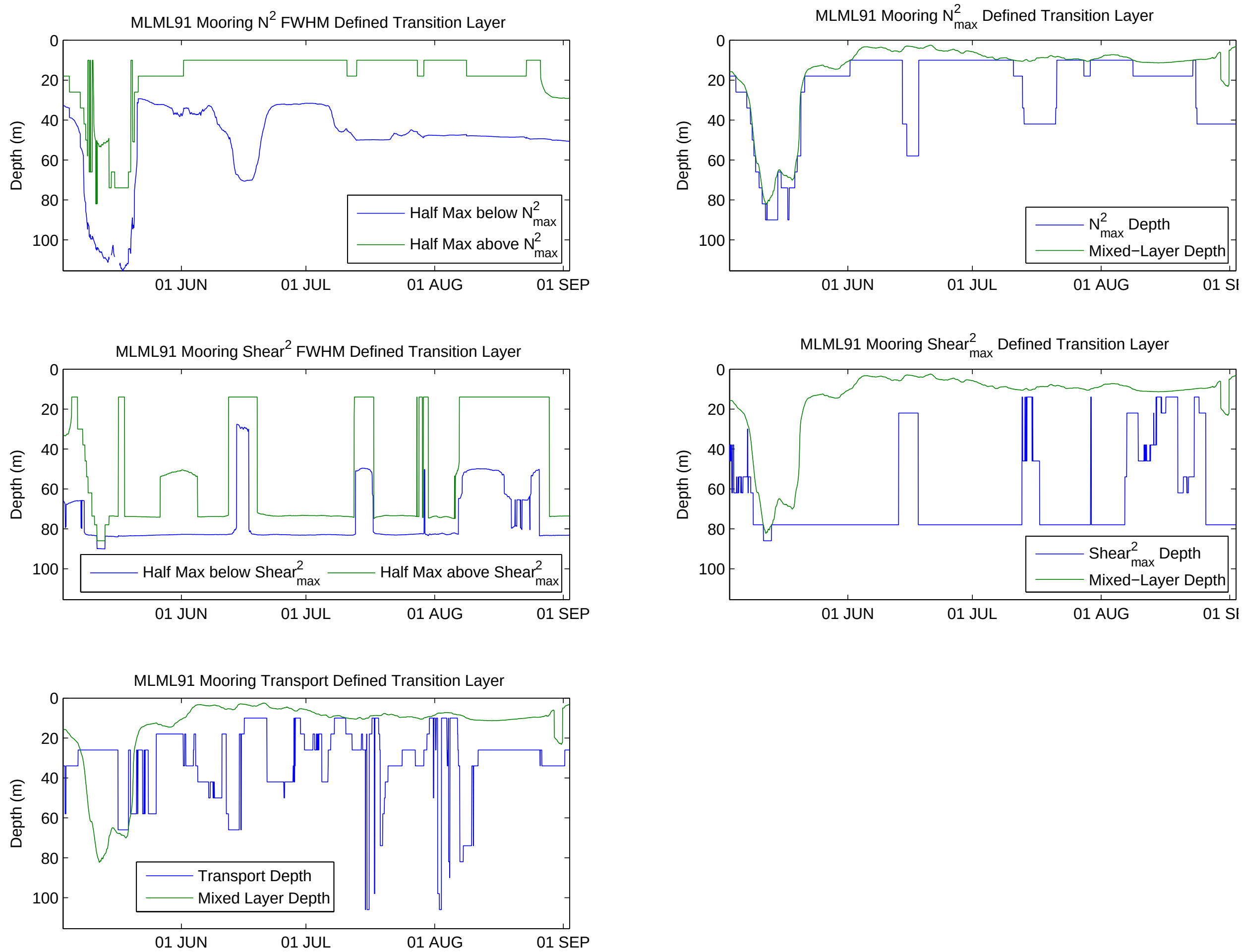

Figure 6: MLML Mooring Transition Layer Thicknesses during April 1991 through September 1991. In each plot, the transition layer is the region between the two curves, with the green curve defining the top of the transition layer and the blue curve defining the bottom of the transition layer. The top left plot shows transition layer defined by N^2_{fwhm}; the top right defined by N^2_{max}; the middle left defined by $shear^2_{fwhm}$; the middle right defined by $shear^2_{max}$; the bottom left defined by the Ekman depth. Note that when the Ekman transport depth is shallower than the mixed layer depth the Ekman thickness definition cannot be used to define the transition layer.

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