Spatiotemporal Variability Relationships of Shallow Cloud Height and Planetary Boundary Layer Height Over the Northeast Pacific Using Satellite Observations and Reanalysis

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Abstract

Over 18 years of satellite data from Multi-Angle Imaging Spectroradiometer (MISR) and 14 years from Global Navigation Satellite System-radio occultation (GNSS-RO), with ERA5 reanalysis temperature profiles, are used to assess the co-variability of cloud and thermodynamic properties of the Northeast Pacific subtropical marine boundary layer. Low cloud top height (CTH) inferred from MISR and planetary boundary layer height (PBLH) inferred from GNSS-RO are well-correlated spatially for all seasons when seasonally-varying mid-latitude grids (temperature at 700 hPa < 4°C) are removed (r=0.83), or when vertical velocity at 500 hPa (ω500) indicates descent (r=0.74). The temporal correlation of PBLH and CTH is highest in the stratocumulus region (r=0.72), with the CTH versus PBLH slope close to one for heights between 0.8 km and 1.6 km of the time series. Seasonal sea-surface to 700 hPa lapse rate (LR) is spatially related with PBLH and more strongly with CTH, and ω500 modulates seasonal CTH-LR relationships. The impact of El Niño Southern Oscillation (ENSO) through teleconnections on the PBL structure is also characterized, with maximum deseasonalized temperature anomalies near or above PBL top (near the surface) during La Niña (El Niño), with CTH, PBLH, and LR anomalies largest during the strong 2015-2016 El Niño. Temperature anomalies above the PBL lead CTH' and PBLH' by 15 and 18 months, respectively, just under half the time scale of the periodicity of an Ocean Niño Index mode (~3.1 years), suggestive of the role of atmosphere-to-ocean exchange manifesting in a deepening PBL during warm ENSO.

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Key Points:

●Northeast Pacific low cloud and PBL heights agree best when excluding profiles with low temperatures above the PBL or rising motion aloft.

● Cloud and PBL heights are enhanced (suppressed) when Oceanic Niño Index or Pacific Decadal Oscillation is positive (negative).

● Temperature anomalies above PBL top may provide forecasting skill up to 1.5 years of marine layer depth and low-topped cloud heights.

Abstract:

Over 18 years of satellite data from Multi-Angle Imaging Spectroradiometer (MISR) and 14 years from Global Navigation Satellite System-radio occultation (GNSS-RO), with ERA5 reanalysis temperature profiles, are used to assess the co-variability of cloud and thermodynamic properties of the Northeast Pacific subtropical marine boundary layer. Low cloud top height (CTH) inferred from MISR and planetary boundary layer height (PBLH) inferred from GNSS-RO are well-correlated spatially for all seasons when seasonally-varying mid-latitude grids (temperature at 700 hPa < 4°C) are removed (r=0.83), or when vertical velocity at 500 hPa (ω_{500}) indicates descent (r=0.74). The temporal correlation of PBLH and CTH is highest in the stratocumulus region (r=0.72), with the CTH versus PBLH slope close to one for heights between 0.8 km and 1.6 km of the time series. Seasonal sea-surface to 700 hPa lapse rate (LR) is spatially related with PBLH and more strongly with CTH, and ω_{500} modulates seasonal CTH-LR relationships. The impact of El-Niño Southern Oscillation (ENSO) through teleconnections on the PBL structure is also characterized, with maximum deseasonalized temperature anomalies near or above PBL top (near the surface) during La Niña (El Niño), with CTH, PBLH, and LR anomalies largest during the strong 2015-2016 El Niño. Temperature anomalies above the PBL lead CTH' and PBLH' by 15 and 18 months, respectively, just under half the time scale of the periodicity of an Ocean Niño Index mode (~3.1 years), suggestive of the role of atmosphere-to-ocean exchange manifesting in a deepening PBL during warm ENSO.

Plain Language Summary:

Two independent space-borne observational data sets characterize how well marine layer top heights correspond with low-level cloud heights over the Northeast Pacific Ocean region. Low cloud heights correlate best with marine layer heights seasonally and spatially when areas

exhibiting mid-latitude behavior of lower temperatures above marine layer top, and hence reduced stability based on reanalysis data, are excluded. Rising motion aloft decreases the capping strength of the marine inversion, less likely constraining clouds to the boundary layer. On interannual time scales, El-Niño Southern Oscillation and the Pacific Decadal Oscillation remotely influence the low-level temperature stability of the Northeast Pacific Ocean, with greater lapse rates, marine layer heights, and low cloud heights during periods of El Niño versus La Niña. During El Niño, temperature anomalies are greatest near the surface, destabilizing the lower atmosphere, with the highest anomalous ocean temperature greatest in spatial scale during the 2015-2016 event, and during La Niña, temperature anomalies are greater near or just above marine layer top, stabilizing and suppressing the marine layer depth and low cloud heights. Temperature anomalies above the marine layer may provide forecasting skill up to 1.5 years of the depth of low clouds and the marine layer.

1 Introduction

The planetary boundary layer (PBL) and low-level clouds are of profound importance both to the climate system and also to the regulation of near-surface air with the free troposphere. Closely related to how well-mixed the PBL is, the PBL height, through its tie to low-level stability, helps determine the concentration of near-surface pollution; deeper PBLs are inversely correlated with near-surface concentrations such as tropospheric ozone (O_3) and O_3 precursors (Dey et al., 2018). Over the oceanic tropics, the PBL height is also inversely related to precipitation owing to the relationship of stronger sensible heat fluxes during the dry season; during wet periods stronger latent heat fluxes move mass above the shallower PBL (Chan and Wood, 2013). In primary low cloud regions, PBL depth also helps control cloud type and coverage (Chan and Wood, 2013; Wood, 2012).

Marine oceanic low-level clouds have a net cooling effect on the climate system, owing to their high reflectivity compared to the ocean surface and only modestly cooler cloud top temperatures (e.g. Boucher et al., 2013; Hartmann et al., 1992; Randall et al., 1984), such that the shortwave cooling effect exceeds the modest longwave warming effect, but how low clouds may change in response to local or remote forcing on a variety of time scales may be critical for helping to constrain climate sensitivity estimates. As clouds and/or the PBL deepen in association with increases in sea-surface temperature (SST), a reduction in the lower tropospheric temperature in the upper boundary layer or near PBL top, or some combination thereof, low cloud breakup may ensue in conjunction with a weakened inversion and increased decoupling and entrainment by cumulus clouds in vigorous updrafts of dry free tropospheric air (e.g. Wyant and Bretherton 1997), making low cloud top height (CTH) and planetary boundary layer height (PBLH) important markers of horizontal cloud cover and the amount of sunlight reaching the ocean surface.

Close to the coast, well-mixed clouds are generally shallowest and topped by stratus or stratocumulus (Sc) clouds, especially during summer when low-level stability is strongest. This is also where CTH and PBLH agree most closely with each other, at least over the Southeast Pacific (Kubar et al. 2020); however, mean CTH is often below PBLH in trade cumulus regions since not all clouds reach the trade inversion (Karlsson et al. 2010). This may also be the case for stratocumulus with underlying cumulus clouds, in which both a weak stable layer exists below the primary inversion base as well as a moist surface layer induced by relatively stronger upward latent heat fluxes. The cumulus clouds detrain into the stratocumulus clouds, and in broken Sc areas, the retrieved cumulus cloud top height is lower than the inversion layer (Zhou et al., 2015). As summarized in Zhou et al. (2015) of the Bretherton and Wyant (1997) study, the transition layer is below the radiatively-driven inversion height and above the surface layer of enhanced specific humidity; the upper part of the PBL thus is decoupled from the lower part (Jones et al., 2011). In such a PBL, the lapse rate from the surface to the lifting condensation level (LCL) is the dry abiabatic lapse rate (DALR), and the decoupled layer, between the surface mixed layer top and PBL inversion height, generally follows a moist adiabat (Wood and Bretherton, 2006).

The variability of low cloud fraction has often focused on the annual cycle (e.g. Klein and Hartmann, 1993; Kubar et al., 2012), though De Szoeke et al. (2016) have demonstrated the importance of the time scale between synoptic and seasonal. Recent work has examined changes in cloud-controlling factors to describe commensurate changes in low cloud fraction; using two decades of Terra and Aqua Moderate Resolution Imaging Spectroradiometer (MODIS) data, Andersen et al. (2022) characterize a reduction in low cloud cover over the Northeast Pacific most concentrated between 13°N-23°N and 140°W-112°W. Corresponding large-scale environmental trends include an increase in SST and decreases in wind speed, subsidence strength, and estimated inversion strength (EIS), and a weak increase in free-troposphere relative humidity. The authors attribute natural variability to the trends. Incidentally, there's a nearly equal and opposite (positive) trend of low cloud cover in the SE Pacific (Andersen et al., 2022). Such north/south asymmetric trends are an amplification of already observed natural distribution of more low clouds over the southeast versus the NE Pacific.

Building on Kubar et al. (2020), hereafter KU20, the goal of this study is to characterize the spatiotemporal variability of CTH and PBLH, focusing on where there is consistency between PBLH and CTH, with results broken down seasonally, and also across the NE Pacific instead of the SE Pacific. While we expect agreement to be best over the shallowest to moderate-depth PBLs, such as stratus, stratocumulus, and the transition to trade cumulus regions, we aim to quantify CTH-PBLH relationships through statistical analysis. We also examine interrelated variables such as the lower tropospheric lapse rate and ω_{500}. Recently, Kalmus et al. (2022) have provided a global analysis of PBLH at the highest horizontal resolution publicly available to date from GNSS-RO, with the annual and diurnal cycle climatologies assessed. Our study is both more regional and addresses PBLH spatiotemporal relationships with satellite CTH measurements from Multi-Angle Spectroradiometer (MISR), in addition to low cloud/PBL-controlling variables of each. Temporally, we examine modes ranging from subannual to annual to interannual. For interannual variability, teleconnections such as El Niño Southern Oscillation (ENSO) and the Pacific Decadal Oscillation (PDO) may be important; during warm (cold) ENSO, SSTs are not only anomalously warm (cold) over the central and eastern equatorial

Pacific, but positive (negative) SST anomalies also extend poleward over the mid-and-high latitudes of the NE Pacific. The anomalous mid-latitude SST spatial patterns associated with both phases of ENSO are similar to those with the PDO, though PDO intrinsically encapsulates lower-frequency variability. We will quantify the role of these SST anomalies and co-located atmospheric temperature anomalies in driving the low-level lapse rate and hence PBLH and CTH anomalies.

2 Data

a. Multi-Angle Imaging Spectroradiomer (MISR)

For each gridded low CTH, we use over 18 years (April 2002 – August 2020) of monthly Level-3 MISR data from the cloud fraction by altitude (CFbA) product at 0.5°x0.5° horizontal resolution with 41 vertical levels and 500 m vertical sampling. The CFbA joint product, originally constructed from the L2 1.1 km nadir cloud fraction, represents the highest-resolution CFbA product of any passive instrument (Kubar et al., 2019; Di Girolamo et al., 2010). Compared to other passive satellites, MISR is particularly adept at measuring geometric cloud height directly without the need for external auxiliary profile data, since MISR is equipped with cameras in nine directions, one at nadir, four in the forward along-track, and four in the aft directions of nadir. We compare MISR CTH data both spatially and temporally to PBLH and lower tropospheric measures of thermodynamic stability. For a more detailed discussion of the technical qualities and specifications of MISR, please see Kubar et al. (2019).

The definition of low CTH is the mean height of all clouds in a 0.5°x0.5° grid between the ocean surface and 6 km, with weighting by the histogram of CF(z). For direct point-by-point comparisons, we linearly interpolate the higher resolution CTH grids onto the coarser GNSS-RO 2°x2° PBLH grids. This CTH vertical range includes possible clouds that are above the mean

PBL, which was also noted in de Szoeke et al. (2016); we employ seasonal temperature and dynamic filters to separate out probable mid-latitude clouds.

b. GNSS-RO

Refractivity profiles retrieved from GNSS-RO measurements, which have high vertical resolution (~200 m) and ~100-km horizontal resolution, contain temperature and moisture information used to deduce PBL top in all-weather conditions (Anthes et al., 2008; Kursinski et al., 2000). Specifically, PBLH is determined from each profile by locating the height of the minimum refractivity gradient below 6 km (Ao et al., 2012; Basha and Ratnam, 2009; Xie et al., 2012). At low to middle latitudes, a large refractivity gradient is largely dictated by the moisture and temperature gradient across the PBL top (Ao et al. 2012; Chan and Wood, 2013). Here, we use monthly-averaged 2°x2° PBLH derived from the JPL v2.6 Level 2 refractivity products from the COSMIC, TerraSAR-X, KOMPSAT-5, and PAZ GNSS-RO missions spanning the period of Jun. 2006– Dec. 2020 (Kalmus et al. 2022).

c. ERA5 Reanalysis

We use monthly SST, low-level temperature profile information, and ω_{500} gridded at 0.25°x0.25° from the European Center for Medium Range Forecasts Version 5 (ERA5) to calculate lower tropospheric lapse rates (LR) (Hersbach et al., 2020). With a decade of development since ERA-Interim, ERA5 has the advantage of updated model physics, core dynamics, and data assimilation, with over twice the horizontal resolution. Note that we use ERA5 SST data for the NE Pacific area, with the teleconnection data selection described below.

d. ENSO and PDO

The Oceanic Niño Index (ONI), one of several ENSO indices, is calculated by the three-month running mean of SST anomalies in the Niño-3.4 region between 170°W-120°W and 5°S-

5°N, with the anomalies computed with respect to 30-year base periods updated every five years, and 2°x2° monthly SSTs from the Extended Reconstructed SSTs (ERSST) version 5 (Huang et al., 2017). ONI is used directly from the from the Climate Prediction Center ENSO data, acquired from https://origin.cpc.ncep.noaa.gov/products/analysis_monitoring/ensostuff/ONI_v5.php. The Pacific Decadal Oscillation (PDO) is frequently characterized by a long-duration ENSO-like pattern of North Pacific climate variability (Zhang et al., 1997; Mantua and Hare, 2002), with some overlapping teleconnection patterns over both the Pacific Ocean and North America with ENSO. The PDO index represents the first mode of the EOF of the SST anomalies of the North Pacific (poleward of 20°N), after removal of the global mean SST, referred to as "residuals" in Mantua and Hare (2002). A positive/warm PDO phase (as represented by the first principle component amplitude) occurs when the western/interior north Pacific is anomalously cool with anomalous high pressure and the eastern north Pacific is anomalously warm, while during a cool, or negative phase, the western/interior Pacific is anomalously warm and the eastern North Pacific is anomalously cool. PDO data for this study were acquired from https://www.ncei.noaa.gov/pub/data/cmb/ersst/v5/index/ersst.v5.pdo.dat, which like the ONI time series, are constructed from the ERSST anomalies; the NCEI PDO index used here similarly adheres to the Mantua PDO index.

3. Spatial Analysis Results

The first part of this paper focuses on the horizontal distribution of PBLH, CTH, and LR as a function of season, including the degree of agreement between PBLH and CTH as well as the goodness of fit between PBLH/CTH and LR, and we also examine the separate roles of temperature at 700 hPa (T_{700}) and ω_{500}.

The maximum PBLH over the region, regardless of season, occurs over the southwestern portion of the domain (Figure 1a, 1d, 1g, and 1j), and the shallowest PBLs are found generally in the east, and more specifically the northeast portion. The shallowest clouds are also found in the eastern portion, with a shift of the shallowest heights north during summer (Figure 1h) and further south during winter and spring (Figure 1b, 1e). The coherence between PBLH and CTH is especially high in the eastern part of the NE Pacific. However, while CTH is broadly higher in the west, maximum CTH is observed in the northwestern part of the domain, with the highest low clouds during DJF, whereas the deepest PBLs occur during SON. The LR distribution generally follows a similar spatial pattern with season as CTH, with a clear maximum in the western/northwestern part of the domain during DJF. Minimum lapse rates are observed during summer, especially along the west coast of the U.S. extending to the west coast of Baja California.

In Figure 1m, we present the annual cycle of PBLH and CTH., Both datasets agree that PBLH and CTH are shallowest during summer, though PBLH maximizes during SON, and CTH during DJF. The amplitude of the annual cycle (maximum minus minimum) is 0.24 km for PBLH and 0.38 km for CTH. We note that estimates of PBLH from reanalysis also suggest maximum seasonal heights during SON (not shown).

The annual cycle of LR (Figure 1n), like CTH, maximizes during DJF, minimizes during JJA, and is second largest during SON. The two components of LR, SST and temperature at 700 hPa (T_{700}), are also presented, with SST lagging T_{700} by a season, e.g. free-tropospheric temperatures maximize during JJA, but SSTs continue to warm from JJA to SON, which is likely due to the large thermal inertia of the ocean. Similarly, T_{700} is lowest during winter (DJF), but SST bottoms out one season later (spring, MAM). The amplitude of SST is smaller than the amplitude of

T_{700}, of 3.14°C versus 4.98°C, respectively, and the peak-to-peak amplitude of the regional LR is about 1.0°C km^{-1}.

In the left panels of Figure 2, we present seasonal scatterplots of CTH versus PBLH, and include seasonal slopes using the least absolute deviation method (LADFIT), Pearson linear correlation coefficient (r), and the root-mean square error (RMSE). As we may have anticipated from the

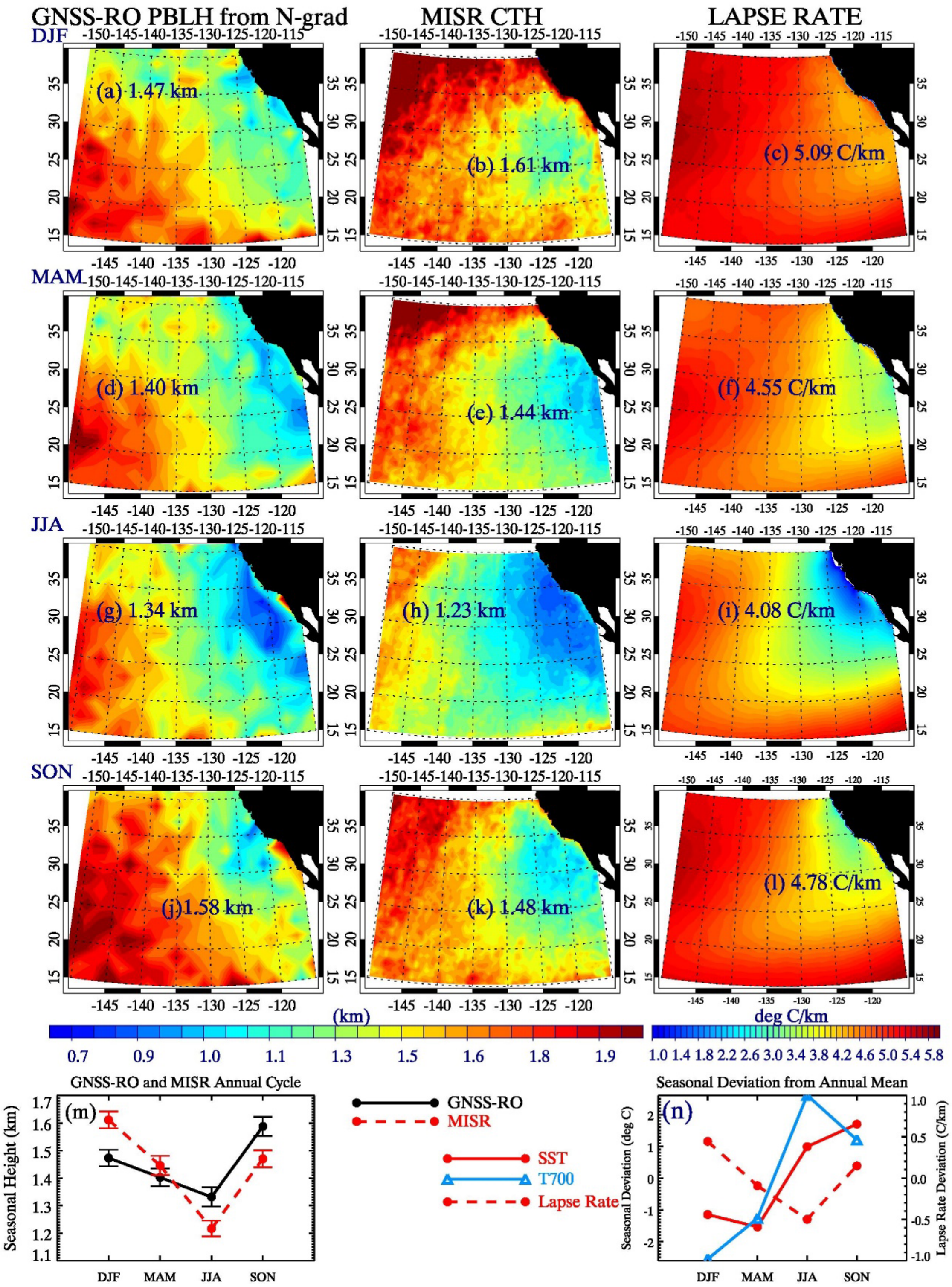

Figure 1. (a), (d), (g), and (j): Seasonally-averaged PBL heights for DJF, MAM, JJA, and SON in km. (b), (e), (h) and (k): Same as (a), (d), (g), and (j), except CTH (c), (f), (i) and (l): Same as (b), (e), (h), and (k) except for LR (°C/km). (m) Annual cycle of PBLH and CTH. (n) Seasonal annual deviation for SST, temperature at 700 hPa, and LR.

seasonal maps in Figure 1, CTH is imperfectly correlated with PBLH, with the least correlation (r=0.30) and largest RMSE (0.297 km) during DJF, and the best fit and smallest RMSE during summer (r=0.83 and RMSE=0.185 km). CTH-PBLH slopes are always below one, meaning that CTH increases more slowly for a given increase in PBLH, though slopes are more similar during MAM, JJA, and SON (0.73, 0.67, and 0.63, respectively) and the slope is greatly reduced during DJF (0.35).

Especially during DJF and MAM, there is a sizeable subset of low cloud tops which substantially exceed PBLH. We highlight where these are spatially with contour maps in the middle column of Figure 2 of PBLH minus CTH; PBLH << CTH primarily in the northern part of the domain during DJF and MAM, which is under the influence of mid-latitude clouds and the seasonal storm track. The greater equatorward shift of baroclinic instability during winter versus summer was shown in Behrangi and Kubar (2012), and also tracks quite well with temperature at 700 hPa (T_{700}), superimposed as unfilled contours in increments of 2°C. In accord with reduced baroclinicity during JJA and SON, there are relatively few clouds above the PBL top during those seasons. During DJF, 24% of CTH observations are greater than 0.3 km larger than PBLH, and 11% are during MAM, and only 1% of grids are during either JJA or SON.

The observation that the slope is less than one for all seasons means that particularly for deeper PBLHs, not all cloud tops reach PBL top. In KU20, MODIS also suggested this relationship in the SE Pacific versus GNSS-RO PBLH (KU20), with daily MODIS CTH leveling off around 2 km for PBLH>2km.

Larger CTH minus PBLH differences are observed when baroclinicity is higher since our method for computing CTH for each grid for each month is weighted by cloud fraction as a function of height for all clouds with tops between 0-6 km. As such, there can be multiple observed

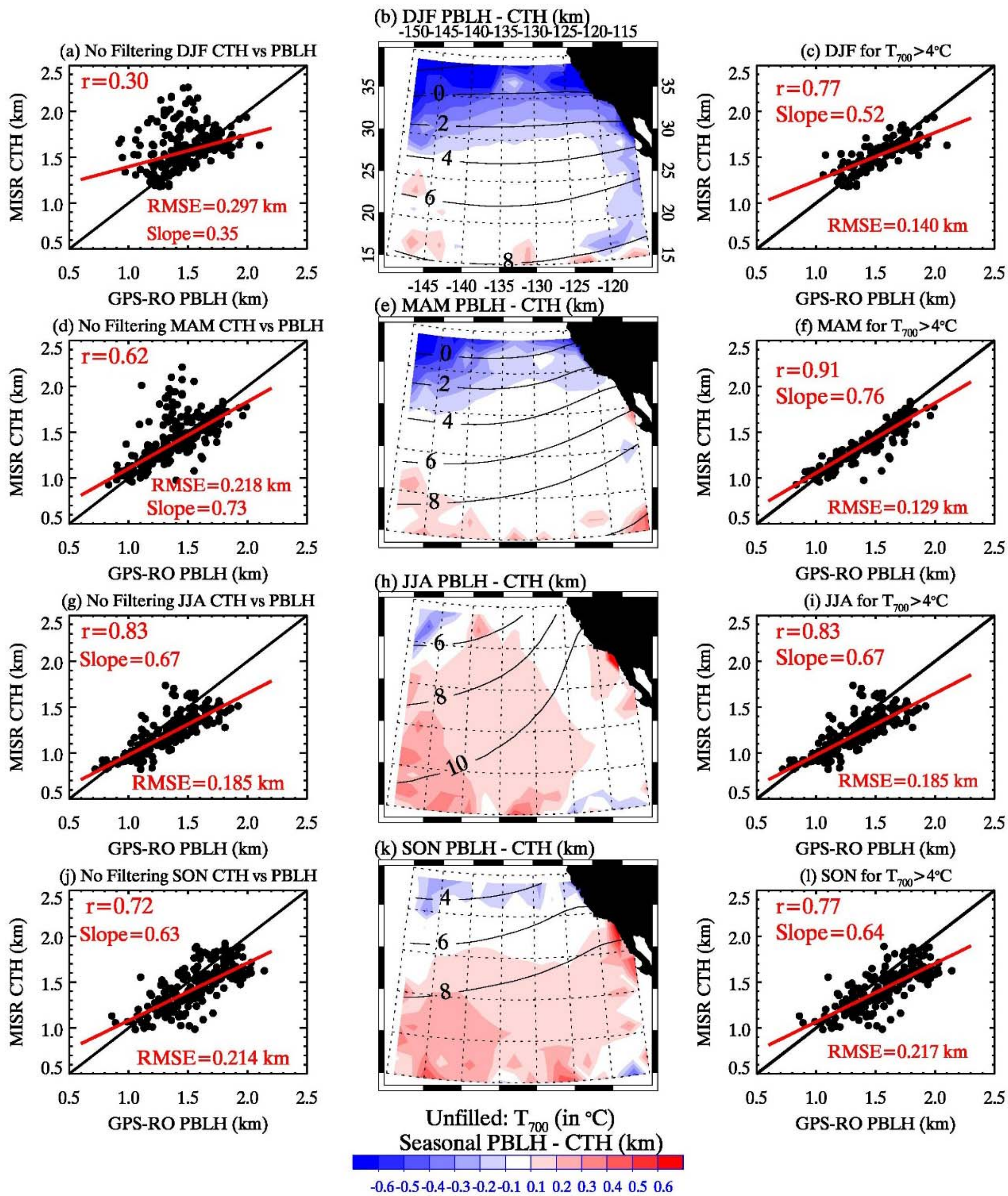

Figure 2. Seasonal scatterplots of CTH versus PBLH for (a) DJF, (d) MAM, (g) JJA, and (j) SON. Middle column: Seasonal PBLH minus CTH (in km) for (b) DJF, (e) MAM, (h) JJA, and (k) SON, depicted by filled contours. White areas indicate differences between -0.1 km and +0.1 km. Unfilled contours denote seasonal 700 hPa temperatures in increments of 2°C. (c), (f), (i), and (l): Same as (a), (d), (g), and (j), except only for seasonal grids with T_{700}>4°C. In the left column and right column, the one-to-one line (black) and the least absolute deviation linear fit (red line) are shown. Also shown in the left and right

columns are the r-value, slope, and the root-mean square error in km. For seasonal grids in which T_{700}>4°C, mean (PBLH-CTH)=14-m for DJF, 60-m for MAM, 115-m for JJA, and 138-m for SON.

cloud tops in a 0.5°x0.5° grid. In contrast, in trade cumulus areas, PBLH > CTH in the southwestern parts of the domain, exceeding 200 m especially where T_{700}>8°C. There is also a small area in which PBLH>CTH near the extreme southern California Coast and Baja California during JJA and SON; this also is an area of strong local SST and LR gradients, with potential effects of GNSS-RO averaging partial land grids.

The right column of Figure 2 shows CTH vs PBLH seasonal scatterplots filtered only for seasonal grids in which T_{700}>4°C, thus preferentially selecting seasonal subtropical grids. CTH-PBLH relationships are most impacted by this filtering during DJF and MAM, which greatly improves the correlation and reduces the scatter; RMSE is only 0.140 km and 0.129 km for DJF and MAM, respectively, and r=0.77 and r=0.91, respectively, much higher than r=0.30 and r=0.62 when the whole domain is considered. The slope for DJF for only grids in which T_{700}>4°C is more similar although still slightly reduced to the other seasons. This suggests that a colder free troposphere is associated with a higher lapse rate and large-scale dynamics connected to mid-level clouds that diminishes the one-to-one agreement between PBLH and CTH for all PBLs/CTHs between 0-6 km.

Next, we wish to understand if related large-scale factors might further explain the presence of cloud tops above PBLH, especially during DJF and MAM, and since our definition of low clouds is generous, we examine the potential impact of ω_{500}, with 500 hPa generally between 5-6 km depending on location. Weaker subsidence, or even weak to modest ascent, may contribute to clouds above the PBL. Figure 3a presents seasonal ω_{500} versus LR scatterplots, with all seasons included in one panel to highlight differences. We invert the y-axis from positive to negative so that going up means weaker subsidence, or for positive ω_{500}, ascending motion. Relationships of

ω_{500} versus LR during JJA (red filled circles) and SON (orange crosses) are more similar to each other; especially during JJA ω_{500} is nearly invariant with increasing LR for 1°C/km < CTH < 4°C/km, with then a stronger reduction in subsidence strength for larger LR; summer is also the only season for mean LR<3°C/km grids are observed. The -ω_{500}-LR slope for SON is slightly stronger, and both MAM and DJF have much larger -ω_{500}-LR slopes.

Seasonal CTH strongly increases with LR for a given season or in the aggregate (Figure 3b), and we show the least-squares exponential fit, with an r-value of 0.88, which is slightly more skillful than a linear fit (r=0.85). Two distinguishing features for DJF and MAM are sharp increases of CTH for a subset of the NE Pacific above the predicted fit for LR just under 5°C/km for MAM and around 5.5°C/km for DJF; this is similar behavior as ω_{500}, with corresponding ascending motion with these LR. The qualitative similarity between panel (a) and panel (b) suggests that free-tropospheric vertical velocity may be modulating CTH-LR behavior.

Seasonal PBLH vs LR has more scatter than CTH vs LR, but similar to CTH, a least-squares exponential fit (r=0.73) is slightly more skillful than a linear fit (r=0.71). One of the main differences, as we may have expected form Figure 1, is that during SON, PBLH tends to be above the predicted values from the least-squares exponential fit; this offset cannot be readily explained by either seasonal LR or ω_{500} differences versus other seasons.

We also compare the behavior of both CTH and PBLH versus ω_{500} (Figure 3d), and see that there is considerable overlap with increasing CTH or PBLH with decreasing free-tropospheric subsidence strength in subsidence regimes, but for ascending motion grids, PBLH is nearly invariant with decreasing ω_{500}, whereas CTH appears to exhibit more of a monotonic increase with decreasing subsidence and increasing ascent.

To make these points even more obvious, in Figure 3f we plot CTH vs PBLH for grids with descent (ω_{500} > 5 mb/day; black dots) and those with near-neutral conditions or ascent (ω_{500} < 5

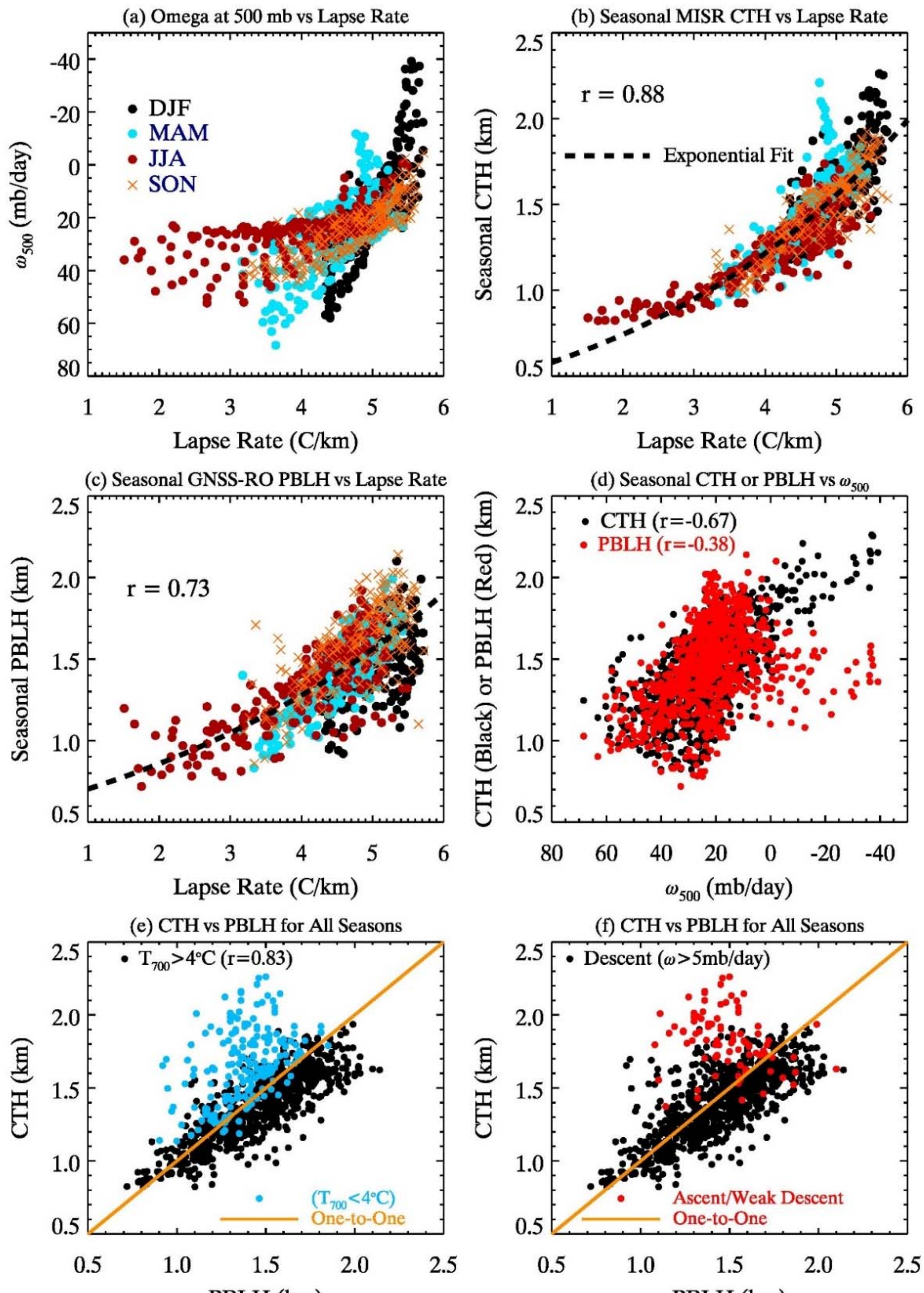

Figure 3. (a) – (c) Seasonal scatterplots versus LR of (a) ω_{500}, (b) CTH, and (c) PBLH, with black dots denoting DJF, light blue dots denoting MAM, red dots denoting JJA, and orange crosses denoting SON.

Best exponential fit lines and r-values given in (b) and (c). (d) Seasonal CTH vs ω_{500} (black dots) and PBLH vs ω_{500} (red dots), with r-values given in legend. (e) CTH vs PBLH for all seasons in which T_{700}>4°C (black dots) and T_{700}<4°C. (f) CTH vs PBLH for descending grids (ω_{500}>5 mb/day; black dots) and weak seasonally-descending/ascending grids (ω_{500}<5 mb/day; red dots). For all grids, r(PBLH,CTH)=0.62, and for ω_{500}>5 mb/day, r(PBLH,CTH)=0.74.

mb/day; red dots), with generally good agreement for descending grids, and CTH usually much larger than PBLH for near-neutral or ascending seasonal grids. When all seasonal grids are included, r(PBLH,CTH)=0.62, but for descending grids with ω_{500}>5 mb/day, r=0.74. Thus, excluding free-tropospheric ascent improves the consistency between the two sets of observations. For a nearly analogous comparison, but with T_{700} as a filter, in Figure 3e we show CTH vs PBLH for our previous constraint of T_{700}>4°C (black) and T_{700}<4°C (blue); for T_{700}>4°C the r-value of all seasons is 0.83, suggesting greater improvement in agreement between CTH and PBLH with a thermodynamic rather than dynamic (ω_{500}>5 mb/day) constraint, though both constraints remove outliers from a presumed linear fit.

4 Temporal and Spatiotemporal Analysis

We next examine time series across the entire NE Pacific domain as well as subregions defined by their percentiles. Percentiles of variables naturally move spatially, offering a measure of distribution changes over time.

We begin with the time series of the 25^{th} and 75^{th} percentiles of monthly PBLH and CTH (Figure 4a), starting in 2006 for PBLH and 2002 for CTH. The 25^{th} percentiles of PBLH and CTH closely track each other in time, with a temporal correlation of r=0.72 (Figure 4e), whereas the 75^{th} percentiles are often out-of-phase by up to a few months; CTH_{75th} peaks near the beginning of each year and $PBLH_{75th}$ peaks during SON. Based on our earlier seasonal spatial analysis, the location of deepest PBLHs (southwestern part of the domain) is not in the same place as the deepest low clouds (northern/northwestern part of the domain). The standard deviation, a good proxy of the annual cycle amplitude, is greater for CTH_{75th} (0.22 km) than for

PBLH$_{75th}$ (0.16 km). Standard deviations of PBLH and CTH are very similar especially for the bottom 50% of the distribution for each variable, above which σ_{CTH} begins to exceed σ_{PBLH} (Figure 4d). The lapse rate standard

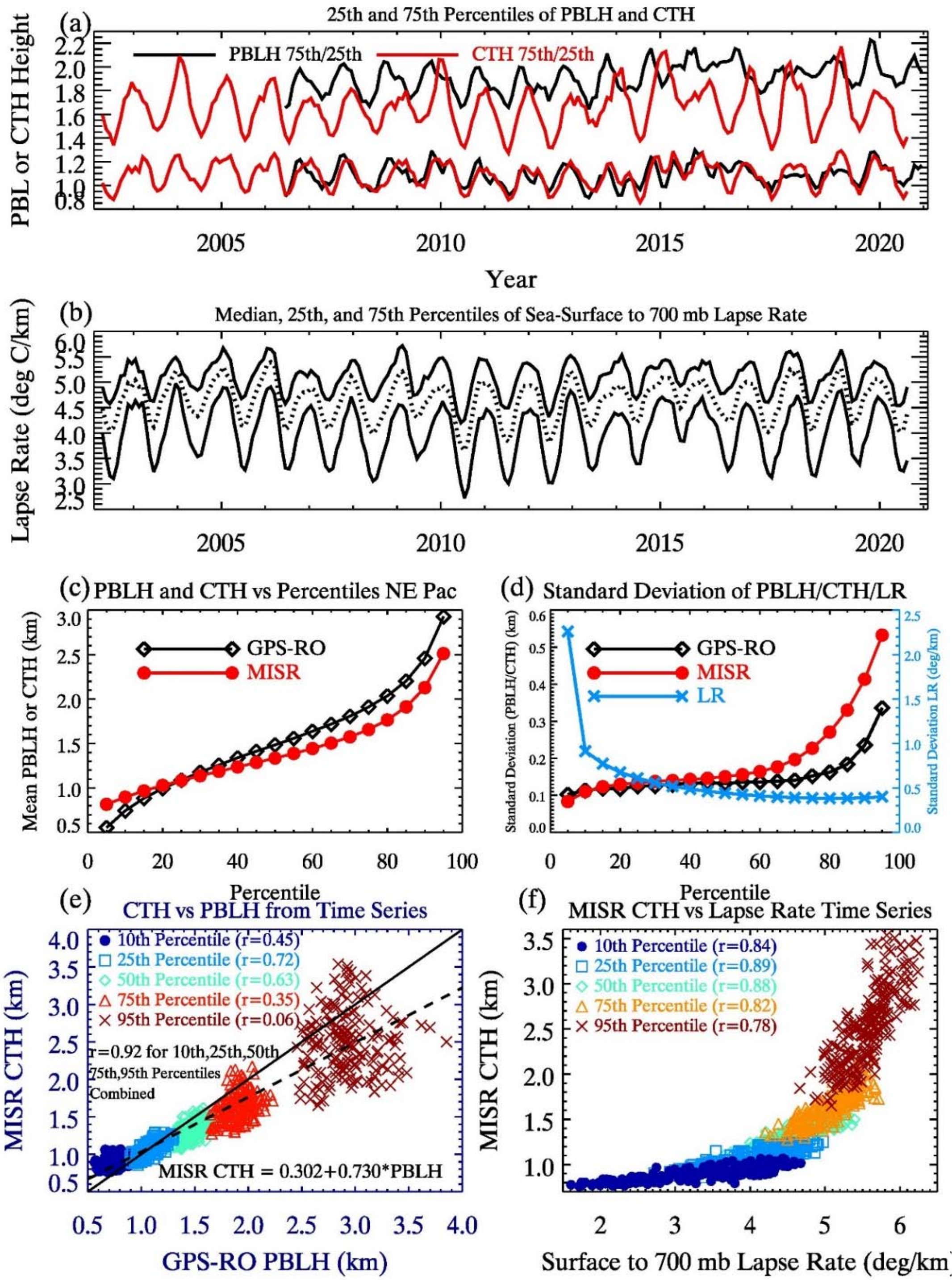

Figure 4. (a) Time series of domain-averaged PBLH and CTH 25th and 75th percentiles. (b) Same as (a), except for LR and also including the median time series. (c) Mean PBLH and CTH vs percentile (d) Standard deviation of PBLH, CTH, and LR versus percentile. (e) CTH versus PBLH for selected percentiles. (f) Same as (e), except for CTH versus LR. In (e), one-to-one and least absolute deviation linear fit lines are shown.

deviation *decreases* with percentile, which is apparent either from Figure 4b or the blue curve in Figure 4d. When we examine the CTH percentiles versus LR percentiles (Figure 4f), any given CTH percentile is fairly well correlated within any LR percentile, with the highest r-values for the 25th-50th percentiles, but the shape of CTH percentiles among different LR percentiles appears to be *exponential* due to the reverse behavior of the standard deviation behavior of each.

We next shift to time series of anomalies, calculated by removing the annual cycle, using a reference climatology at each grid or subregion for each month. We present time-longitude Hovmöller diagrams latitudinally-averaged between 15°N-40°N. The focus is on interannual variability, with the possible identification of west-east propagation of features of anomalies on shorter time scales. First, we regrid ERA5 variables to MISR CTH' resolution, and perform a boxcar average of width three in each direction for all variables, meaning 3-month smoothing in time and 1.5° smoothing in longitude.

The Hovmöllers in Figure 5 include (a) CTH', (b) LR', (c) SST', and in panel (d), ONI is presented with red dots denoting months of El Niño (ONI>0.5°C), black dots denoting neutral conditions (-0.5°C<ONI<0.5°C), and blue dots denoting La Niña (ONI<-0.5°C). Due to the greater sparsity, we are not able to present PBLH Hovmöller diagrams. Particularly for CTH' and LR', periods of positive anomalies tend to coincide temporally with El Niño periods, and periods of negative anomalies coincide temporally with La Niñas. We draw red and blue boxes during periods of more sustained (temporally) positive and negative anomalies for CTH', LR', and SST'.

The strongest El Niño of the record peaks in late 2015/early 2016 (Figure 5d), which coincides with a period of enhanced CTH', LR', prolonged high SST', and even warm T700' (not shown). There appears to be propagating west-to-east positive CTH' and LR' from early 2015 in the west to the eastern boundary in late 2015/2016, but there is also localized east-to-west movement

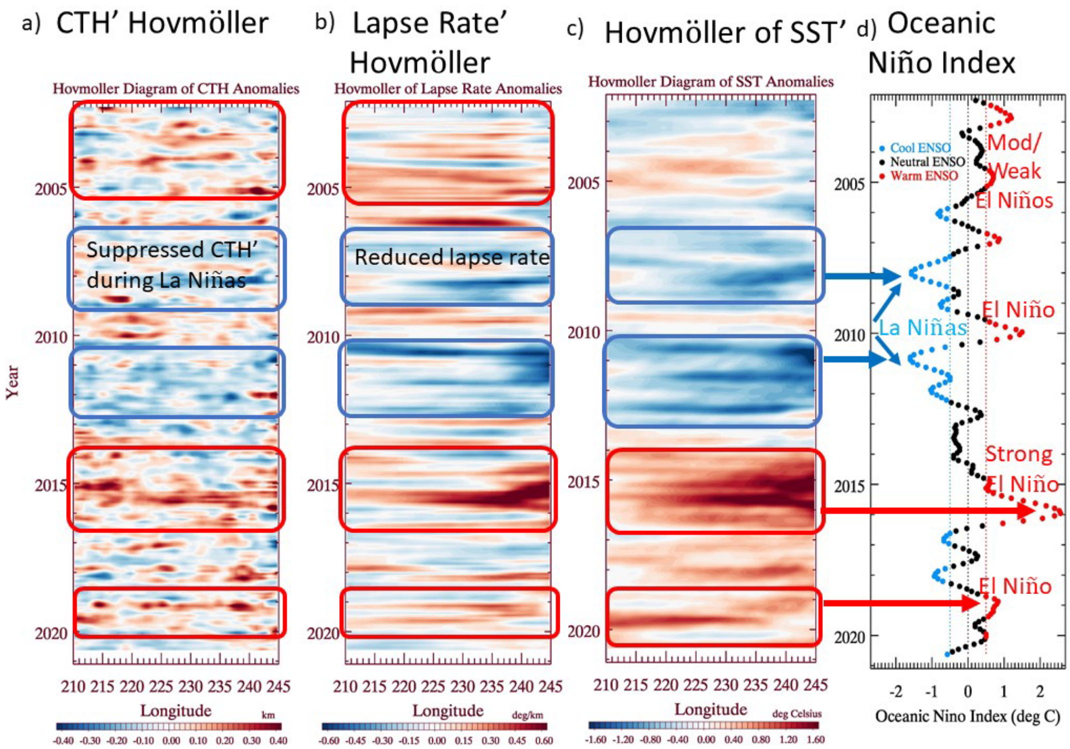

Figure 5. Hovmöller diagrams across the NE Pacific domain (15°N-40°N) for (a) CTH', (b) LR', (c) SST', and d) ONI. Red (blue) boxes in (a), (b), and (c) designate when anomalies tend to be positive (negative), corresponding with periods of more active El Niños (La Niñas). In (d), thin red dashed line represents threshold above which El Niños exist (ONI>0.5°C), and thin blue dashed line below which La Niñas (ONI<-0.5°C) exist. Anomalies are calculated by removing the annual cycle from the reference period for each dataset.

especially of LR' and SST' from the coast in early 2015 westward later in the year. High SST anomalies may also be connected to the broader marine heat wave over the northeast Pacific from 2013-2015 (Myers et al. 2018). Consistent with a Terra-MODIS analysis of low cloud fraction by Myers et al. (2018), MISR indicates suppressed low cloud fraction starting in 2014, with the least amount of low cloud in much of 2015 (not shown).

Spatiotemporally, SST' and T700' are weakly correlated (r=0.38), and 14% of the variance of SST' can be explained by T700'. SST' is more spatiotemporally correlated with LR', with r=0.63 (r^2=0.40), but without temporal smoothing, T700' is more strongly anticorrelated with LR' (r = -0.71). This suggests a smaller intrinsic temporal autocorrelation of free-tropospheric temperature compared to the ocean surface. In contrast, T700' is only weakly anticorrelated with CTH' (r=-0.25) (no smoothing), whereas CTH' and SST' are modestly more correlated (r=0.37) using a boxcar average of width 3x3, and r=0.48 for LR' and CTH' for the same smoothing.

West-to-east propagation of LR' and SST' precedes some La Niñas; in mid-2010 a negative LR anomaly travels from west-to-east across the domain, leading to sustained negative LR' for more than a year in the east; similar propagation of SST occurs in concurrence. When ONI denotes La Niña from late 2010 through early 2012, a double-dip La Niña, there are three instances of negative pulses of negative LR' and SST', some apparently propagating in a west-to-east manner and some occurring simultaneously across the domain. Despite more noisiness, during this period, CTH tends to be shallower than normal as well.

a. Vertical Structure of Temperature Anomalies over Time, relationship to ENSO, and LR', CTH', PBLH' Anomalies

To consider possible lagged ocean-atmosphere correlations, time series of temperature anomaly profiles are computed and presented in Figure 6a, smoothed using a five-month central moving mean. With the exception during several El Niño events, prior to 2013, the lower troposphere is generally cooler than normal ($\overline{T}$'= -0.27°C), followed by warmer than normal conditions after 2013 ($\overline{T}$' = 0.36°C), with especially strong positive anomalies in the years preceding and in conjunction with the late 2015/early 2016 El Niño, in which the five-month running-mean ONI exceeded 2°C for six months, with a peak of 2.53°C There are also some instances in which anomalies first emerge above the surface or in the lower free troposphere and then propagate downward to the surface; this is apparent in mid-2008 in which near-neutral to weak positive T' aloft reaches the surface by mid-2009 through early 2010 in relation to that year's moderate El Niño. Three pulses of positive T' aloft, in early 2013, early 2014, and then early 2015 propagate downward, reaching

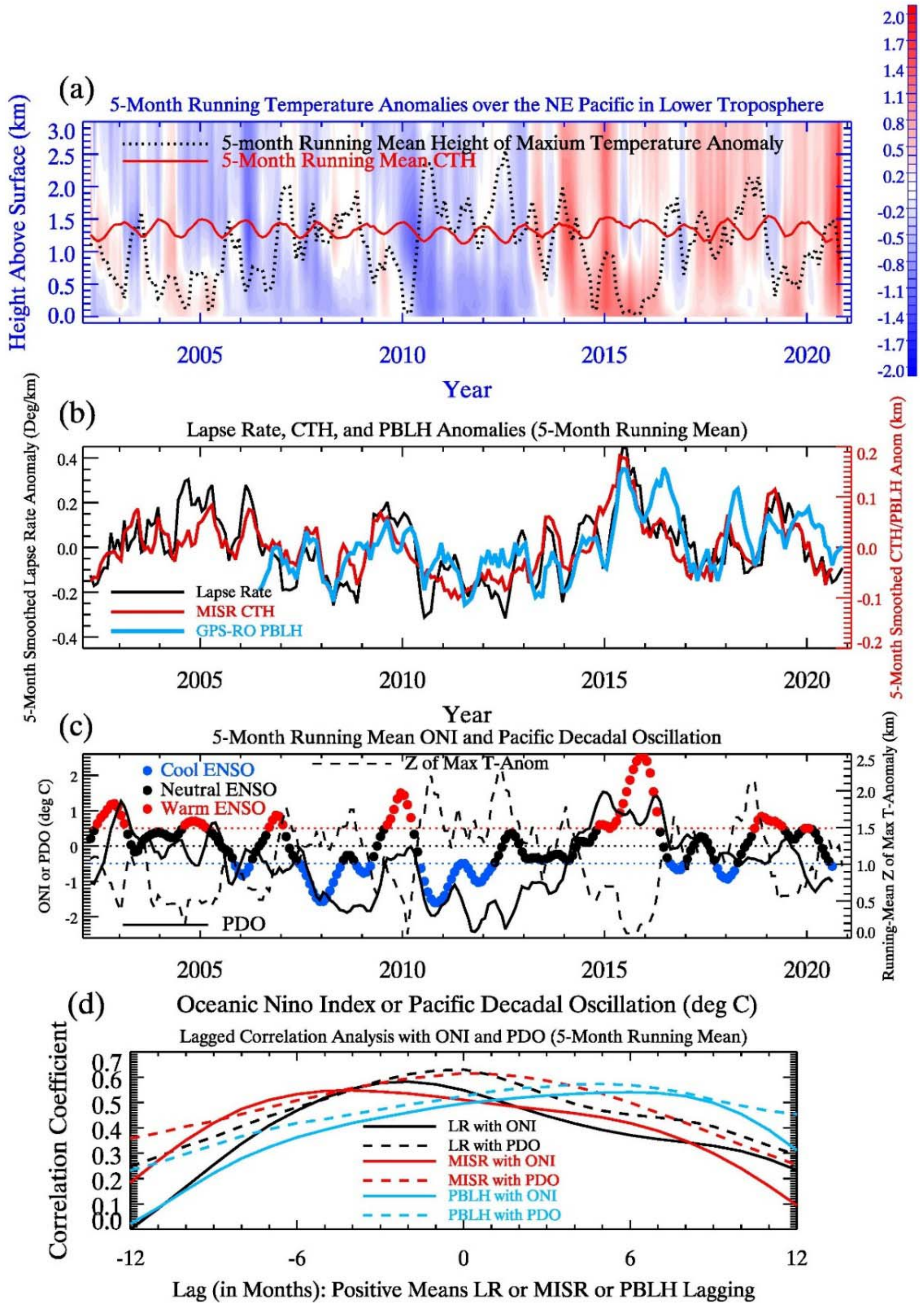

Figure 6. (a) 5-month running mean time series of temperature anomalies as a function of height, with a dashed line depicting the smoothed 5-month running mean of the height of the maximum temperature anomaly for each profile between 0-3 km. Also shown is the running mean CTH. (b) 5-month running mean time series of LR' (black curve), CTH' (red curve), and PBLH' (blue curve). (c) 5-month running mean of ONI and PDO, with 7-month running mean of the height of maximum temperature anomaly. (d) Lagged correlation analysis of LR', CTH', and PBLH' with ONI or PDO (using a 5-month running mean of each). Positive lag means LR', CTH', or PBLH' lagging.

the surface by mid-to-late 2015 leading up to that season's strong El Niño. We generalize these lead-lag relationships momentarily.

Another way to see the changes in the vertical structure of T' is by examining the mean height of the maximum temperature anomaly in the lowest three km of the troposphere, shown in Figure 6a using a 5-month running mean (dashed line). During positive ONI periods, maximum T' is close to or near the surface; this is the case in early 2003 (moderate El Niño), late 2004 and again in early 2005 (weak El Niño), early 2010 (moderate El Niño), late 2014 (preceding a weak El Niño), and late 2015 (strong El Niño). During a few weak El Niño events (e.g. late 2006-early 2007, 2018-2019), max T' remains above the surface by a few hundred meters, perhaps a reflection of weaker teleconnections in the NE Pacific during those events.

The opposite occurs during La Niña (cold ENSO) events, with maximum T' typically near or above the median PBL top across the NE Pacific, with the strongest La Niñas of the record during late 2007/early 2008 and late 2010/early 2011. The elevated height of maximum T' in mid-2012 coincides with neutral conditions and an extended period of cold PDO values of less than -2°C (Figure 6c), which start increasing by 2013. While the PDO and ENSO often are in phase with each other (r=0.49 with an 5-month running mean of the 42-year datasets), they need not be; between 2002-2020, mean ONI was slightly positive (0.04°C), and mean PDO modestly negative (-0.50°C).While the longer-term shift towards warmer lower tropospheric temperatures from 2013 onwards might be related to the shift from negative to positive PDO, in recent years PDO has been generally neutral, then moving back to negative at the end of the record (Figure 6c).

Coincidentally, mid-2012 is characterized by the most suppressed LR' of the entire record; CTH' was a minimum the summer prior, with a bit of recovery by mid-2012, though with continued anomalously negative values.

The strong El Niño through early 2016 transitioned to a weak La Niña in 2016-2017 and again in late 2017-2018, with corresponding increases in the altitude of maximum T'. A stronger signal of the elevated height of maximum T' emerges by mid-2018; which is followed by an abrupt shift to near-surface maximum T' by early 2019 following the formation of a weak El Niño during late 2018 and early 2019.

Near-surface maximum T' generally coincides with positive CTH', PBLH', and LR' (Figure 6b); suggestive of a destabilization of the lower troposphere with maximum heating near the surface. When the altitude above the surface of maximum T' increases, the PBL stabilizes, since the anomalous warmth is near or above PBL top, representative of a stronger mean inversion, and shallower low clouds and PBL heights. The temporal coherence of CTH', PBLH', and LR' is generally strong, with r(PBLH', CTH')=0.63, r(LR',PBLH')=0.69, and r(LR',CTH')=0.78, calculated from 5-month running mean anomalies.

At times, CTH', PBLH', and LR' maximize or minimize during mid-year, out-of-phase from the maximum ONI signal. We quantify this with lagged correlation analysis in Figure 6d. Both CTH' and LR' lead ONI maximally by four months and two months, respectively, with maximum correlation values of 0.55 and 0.58, respectively. SST' also leads maximum ONI by four months, with a similar r-value (not shown). In contrast, CTH' and LR' maximally correlate with PDO at zero lag, with r=0.62 and 0.63, respectively.

In contrast, PBLH' is slightly more correlated after peak ONI; PBLH' peaks about six months following the primary ONI signal, and about five months following peak PDO. We also see this lagged behavior by direct examination of the PBLH' time series; for instance, during the summer of 2016, months after the strong El Niño peak, PBLH' remains as high as the summer prior, whereas CTH' and LR' substantially decrease. Overall, CTH' is maximally correlated with PBLH' when CTH' leads by two months (not shown).

b. Lagged Correlation Profiles

Next, we employ a rigorous filtering approach and examine lagged temperature anomaly correlation analysis with CTH', PBLH', and ONI, using the Savitzky-Golay Filter, henceforth SG-Filter. This weights the center points most, with a degree of tapering and slightly negative weighting for points further away. A boxcar filter, in contrast, weights points of n-width about a center (either temporally or spatially or both) equally. The SG-filter helps improve the signal-to-noise ratio.

In Figure 7, we present lagged correlations between either T'(z) or geopotential height anomaly (Z') with CTH', PBLH', and ONI, and show filled contours in panels (a) through (d) for correlations which exceed the 90th percentile confidence levels. These confidence levels consider the temporal autocorrelation of the variables as in Bretherton et al. (1999) by calculating the effective sample size (ESS, T^*_{XY} below) as follows:

$$T^*_{XY} = T\,\frac{1-r_1 r_2}{1+r_1 r_2} \qquad (2)$$

where T^*_{XY} is the effective sample size for the two time series, *X(t)* and *Y(t)*, which can be CTH', PBLH', ONI, etc. In (2), r_1 and r_2 are the temporal autocorrelations at one month of *X(t)* and *Y(t)*, respectively.

In addition to the above ESS of paired variables, (2) can analogously be applied to a single variable via $T^*=T(1-r^2)/(1+r^2)$ (Bretherton et al., 1999). For an SG-Filter of width three, there are effectively 3.5 independent measurements of PBLH' per year, and 3.75 per year for CTH'. In contrast, for *unsmoothed* SST', there are effectively 17 independent observations throughout the period, thus approximately one each year.

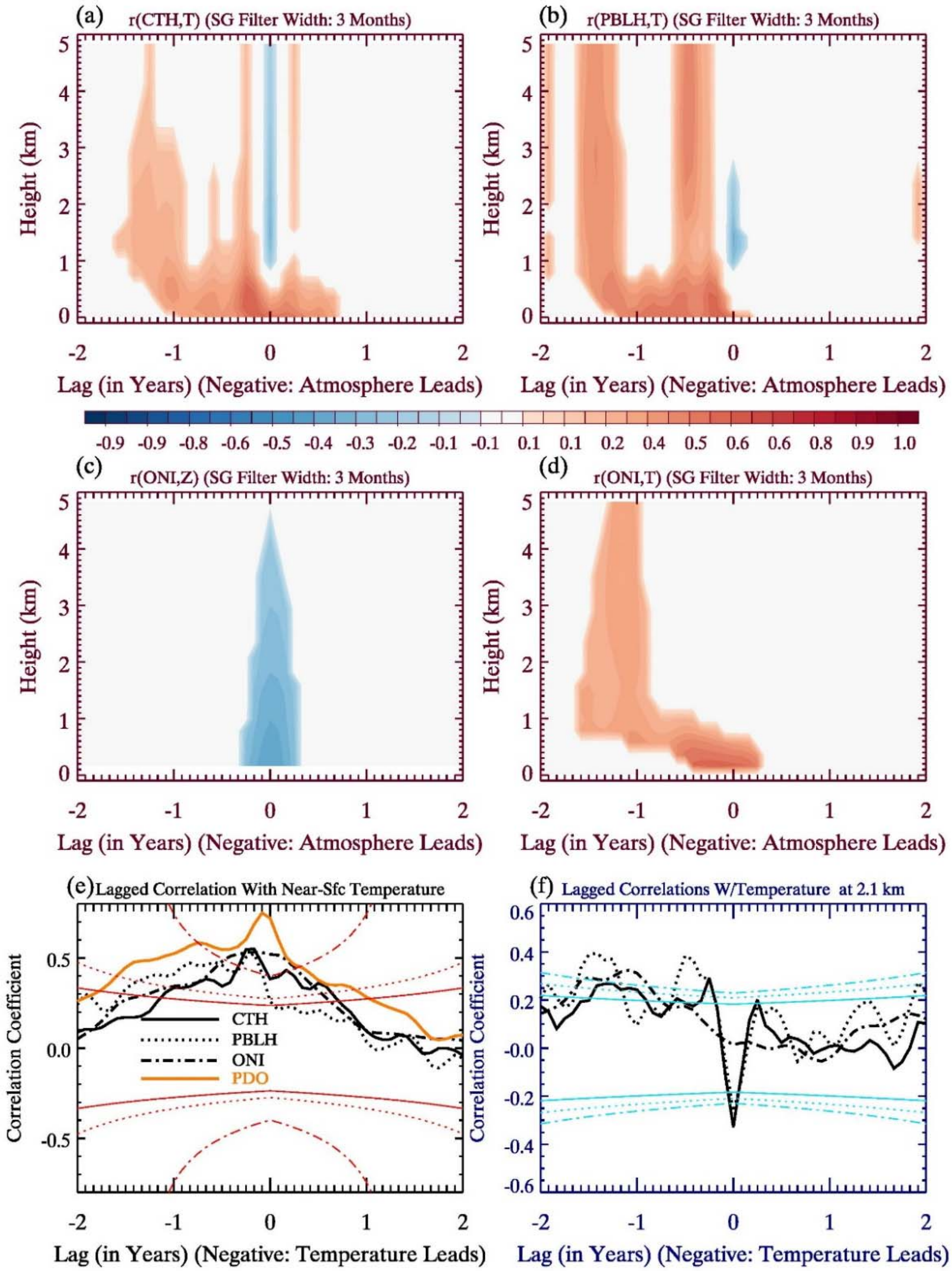

Figure 7. Paired lagged correlations with height for (a) CTH' and T'(z), (b) PBLH' and T'(z), (c) ONI and geopotential height anomalies (Z'(z)), and (d) ONI and T'(z). For each, a Savitzky-Golay (SG) Filter with width of three months is used, in which the weighting coefficients are 0.49 at lag zero and 0.34 at lags of +/- one month. Filled contours are only shown in (a) – (d) when lagged

correlations exceed the 90th percent confidence levels. (e) Lagged correlations with near-surface temperature. Red curves show critical correlation coefficients above/below which correlations are statistically significant at the 90th confidence level. (f) Same as (e), except temperature at 2.1 km; blue curves (and corresponding styles) indicate critical correlation coefficients.

The critical correlation coefficient above which the absolute value of the paired correlation must exceed the 90% confidence level is computed as:

$$Corr_{crit} = \frac{1.64}{\sqrt{ESS - lag(t)}} \tag{3}$$

ESS in (3) comes from (2), and *lag(t)* ranges from -24 to +24 months. Statistically significant correlation is more difficult to achieve with increasing lag between the two variables of interest. In Figure 7a, the correlation profile is presented of CTH’ and T’(z), with negative lag indicative of atmospheric T’ or SST’ leading CTH’. At zero lag, CTH’ is positively correlated with low-level T’ and negatively correlated with T’ in the upper part of the PBL and the free troposphere; suggesting an anomalously unstable profile. There is a tendency for T’ at low altitudes to lead CTH’ (Figure 7a), with T’ near the surface and aloft leading by three months and then at 12-15 months. CTH’ also can lead low-level T’.

The lagged-correlation analysis between T’ and PBLH’ is qualitatively similar at zero lag as between T’ and CTH’ (Figure 7b), with strongest negative correlations between 1 km and 2.5 km. At 2.1 km, T’ is negatively correlated with PBLH’ and CTH’, with r around -0.3 (Figure 7f). In Figure 7b, there are leading atmospheric T’ modes aloft, but with longer lead times with PBLH’ (than CTH’) of about 6 months and 18 months. However, near surface T’ leading PBLH’ by about three months is similar to the correlation of T’ with CTH’ (Figure 7e).

During El Niño, lower-than-normal geopotential heights are present in the NE Pacific at zero lag, with correlations strongest near the surface, but extending upward statistically significantly to nearly 5 km (Figure 7c). Given anomalous counterclockwise flow, this is consistent with positive SST’/low-level T’ with ONI given the anomalous southerly flow in the

NE Pacific. Thus, a more active storm track coincides with positive ONI (and a less active one with negative ONI). Aloft, positive T', between 1 km and the free troposphere leads ONI by 12-15 months, suggesting an atmospheric mode well-before ONI reaches its peak (Figure 7d; Figure 7f).

In Figure 7e, the correlation of T' near the surface with ONI is somewhat broader (than between near-surface T' and CTH' or PBLH'), with a slight tendency for T' to lead slightly. This is also the case for the PDO, though with higher correlation.

c. Fast-Fourier Transform (FFT) Analysis of Dominant Temporal Modes

To evaluate temporal modes of the variables discussed over the NE Pacific, we remove any possible trend via a best linear fit approach and then apply FFT analysis by solving the following, similar to Stine et al. (2009) and Kubar et al. (2012):

$$Y_X = \frac{2}{N}\sum_{t=0.5}^{N} \exp\left(\frac{2\pi i t}{N}\right) x(t + t_0) \qquad (4)$$

In (4), N is the total number of months in each of the time series, which is 221 for CTH, 173 for PBLH, 224 for 18-year ONI and SST time series, and 505 for the 42-year PDO and long ONI time series. The factor of two incorporates positive and negative frequencies.

In Figure 8a, we present the fraction of total variance explained by either the 50th percentile for CTH, PBLH, and SST, and the indices of ONI or PDO, as a function of period (in years); for a given variable, the integrated fraction of total variance equals one. As no bandpass filtering is done, the annual cycle (period of one year) stands out especially for SST (77% of the total fraction of variance explained), MISR CTH (46%), and to a lesser extent GNSS-RO PBLH (24%). Note the different vertical scale for SST compared to the other variables. There is also higher frequency variability for PBLH and CTH; a half-year mode explains nearly 18% of the total variance of PBLH, and 8% of the total variance of CTH.

Weak modes of multi-year periodicity of CTH and PBLH, with small peaks at ~3-years explaining 3% of the total variance, coincide with a roughly 3-year ONI mode that is obtained by either analyzing the 18-year time series (2002-2021) or the 42-year ONI time series from 1979-2021. Spectral analysis of both ONI time series yields a 1.5-year ENSO mode; the 42-year ONI contains multiple spectral peaks between 2.2-4.7 years, whereas the 18-year ONI has a broad, nearly flat peak centered around 6 years. The PDO overlaps to some extent with the ONI, especially at 4-5 years, though the most prominent PDO mode is an 8-10 year mode. The e-folding time of the autocorrelation of ONI of 6 months is about half of the PDO (11 months). Over all periods, the 42-year ONI time series has a mean periodicity of 3.9 years, the 18-year ONI time series a periodicity of 2.8 years, and the PDO 5.2 years. For a thorough exploration of different ENSO modes, including temporal and east versus central Pacific El Niño flavors, see both Chattopadhyay et al. (2019) and Kim et al. (2012).

To further examine the behavior of temporal modes of CTH and PBLH across different portions of the NE Pacific, we plot the fraction of variance explained by subannual modes (0.2-yr to 0.8-yr), annual cycle (0.8-yr to 1.2 yr), and multi-year (1.2-yr to 7-yr) modes as a function of percentile. The shallowest PBLs/clouds (5th percentile) are dominated by greater subannual variability than deeper PBLs/clouds, explaining over 70% and 60% of total variance for PBLH and CTH, respectively. For a given percentile, the fraction of variance explained by subannual variability systematically is higher by about 0.15-0.2 for PBLH versus CTH (mean difference of 0.2); the annual cycle is relatively more important for low cloud height variability than for PBLH.

Finally, while multiyear variability is relevant, compared to faster modes, it only explains about 6%-17% of the total variance of both PBLH and CTH. When the annual cycle is removed, however, the interannual mode overall is approximately twice as important, with some sensitivity (especially for CTH) to the regime (percentile) (not shown).

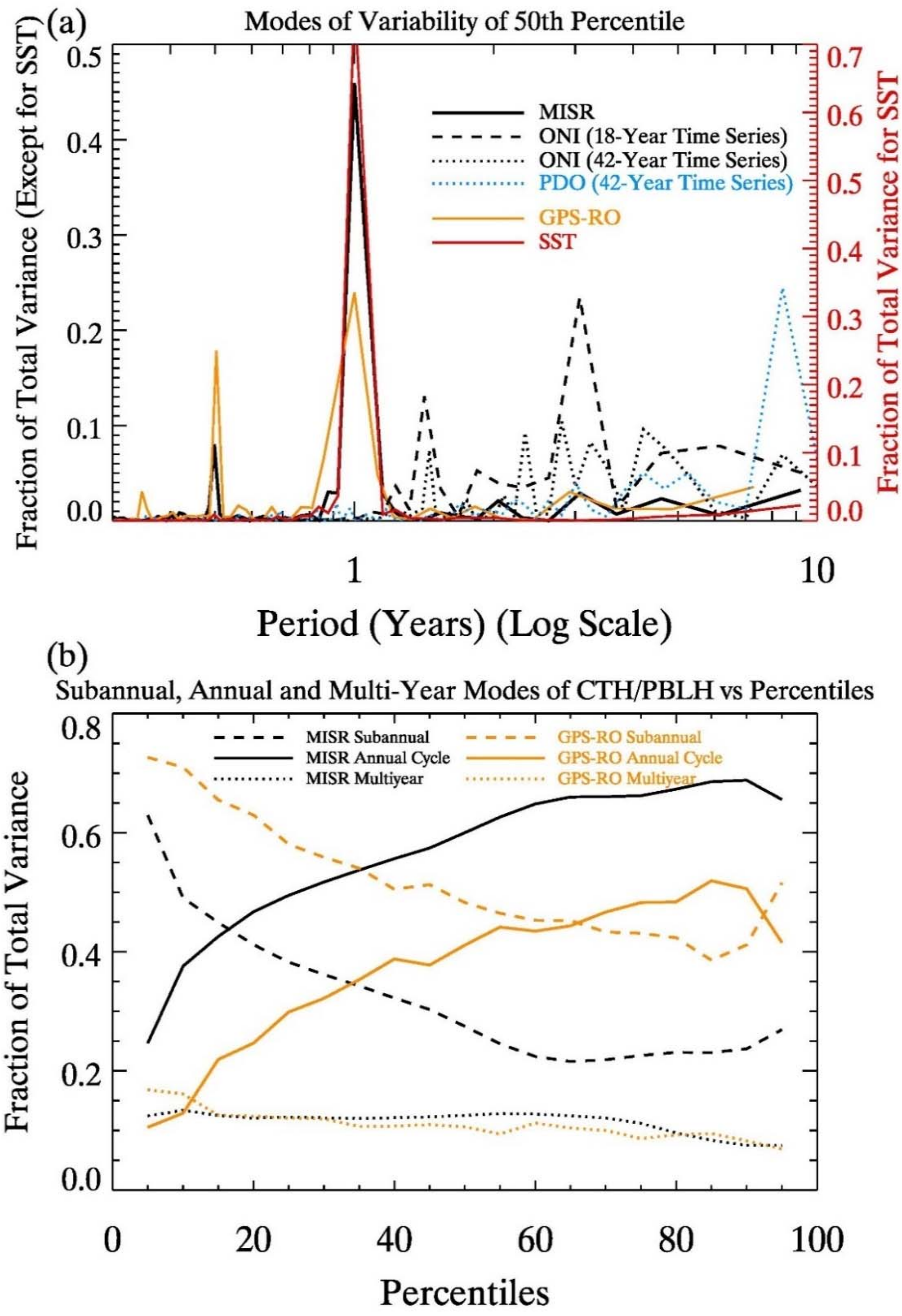

Figure 8. (a) Modes of variability in years (period) at the 50th percentile for CTH, PBLH, SST, ONI, and the PDO time series using the fast Fourier Transform (FFT) function. The ONI FFT analysis is based on both 42 years and 18 years; PDO is based on 42 years. (b) Fraction of

variance explained by subannual (0.2-yr to 0.8-yr), annual cycle (0.8-yr to 1.2-yr) and multi-year modes (1.2-yr to 7 years) for PBLH and CTH percentiles.

5 Discussion and Summary

In this study, we have presented a spatiotemporal analysis of PBLH from GNSS-RO, CTH from MISR, and temperature profile data with a focus on the SST to 700 hPa LR from ERA5 reanalysis data to characterize PBL and cloud height variability on seasonal to interannual time scales over the Northeast Pacific. Building upon previous work, our analysis indicates that PBLH and CTH are most spatiotemporally coherent when seasonal temperatures aloft (at 700 hPa) are greater than 4°C, helping to filter out the effects of mean-tropospheric ascent and the storm track, with the most improvement during DJF and MAM. The best agreement between PBLH and CTH is over stratus and stratocumulus regimes, and mean CTH is below PBLH in the southwestern part of the domain where trade cumulus and shallow convective clouds dominate.

Both PBLH and CTH are spatially correlated with LR seasonally with r(LR,CTH)=0.88 and r(LR,PBLH)=0.73 for all seasons using exponential fits. A subset of low clouds during DJF and MAM have heights above the anticipated best (LR, CTH) fit, which are modulated by stronger upward vertical velocity at 500 hPa (ω_{500}). Seasonal CTH monotonically increases with decreasing ω_{500}, whereas PBLH is fixed at about 1.5 km for near-neutral or ascending seasonal grids at 500 hPa. For all grids and all seasons, r(PBLH,CTH) = 0.62, whereas for ω_{500} > 5 mb day^{-1}, r=0.74 when considering all seasons, and for seasonal T_{700}>4°C, r=0.83.

Consistent with good spatial coherence between PBLH and CTH over shallower PBLs, the 25th percentile time series of CTH and PBLH agree well with each other in terms of annual cycle amplitude (r=0.72). The temporal correlation gradually degrades above the 50th percentiles in part due to different locations of the deepest PBLs versus the deepest CTH, and annual cycle amplitudes of CTH for percentiles above the 60th exceed those of PBLH annual cycle amplitudes. While CTH is well correlated temporally with LR, percentiles of CTH versus LR resemble an exponential increase of CTH since the standard deviation of CTH increases with percentiles.

Hovmöller diagram analysis reveals that CTH', LR', and SST' tend to be positive during periods of El Niño or warm ENSO in general, and negative during periods of La Niña or cold ENSO in general. Spatiotemporal correlation between CTH' and LR' is higher than between CTH' and SST', though spatiotemporal r-values increase for each pair with additional data smoothing. While CTH' is weakly correlated with T700', LR' and T700' are well-correlated spatiotemporally with no smoothing (r = -0.71), suggesting that troughs associated with cold temperatures aloft serve to strongly enhance regional lapse rates at the monthly time scale.

There are instances of west-to-east propagation of positive CTH', LR', and SST' across the analyzed domain, especially preceding the strong 2015-2016 El Niño event, and also of negative LR' and SST' during persistent negative ONIs (2011-2013). In general, the largest anomalies and temporal standard deviations of CTH', LR', and SST' tend to be observed closer to the coast during either phase of ENSO than over the open ocean.

Interannual variability analysis of CTH', PBLH', and LR' shows temporal correlation among all three variables, largely in concert with both ENSO and the PDO. Especially during the strongest El Niño (2015-2016), but also some other ENSO events, CTH' and LR' tend to peak the summer before the peak of ENSO during the subsequent winter, though this leading of low clouds and lapse rate is not always the case; CTH' and LR' are slightly more in phase with the PDO, whereas PBLH' lags both indices by a few months.

We also show that the height of the maximum temperature anomalies in the lower 3km of the troposphere oscillates between near or above the PBL top during La Niña and near the surface during El Niño, suggesting the mechanism of shoaling (deepening) of the PBL during La Niña (El Niño) through the stabilizing (destabilizing) effect of the PBL and lower free troposphere. Lower tropospheric temperature anomalies tend to be negative more often than not prior to 2013 (T'=-0.27°C), consistent with a decreasing PDO during that period, with then sustained positive temperature anomalies from 2013 onward (T'=0.37°C) , and a higher mean value of the PDO. There is also stronger 500 mb subsidence pre-2013 (23.5 mb day^{-1}) versus 2013 onward (19.0 mb day^{-1}). Our results suggest the profound influence of both the teleconnections associated with tropical SST (ENSO) and the broader North Pacific (PDO) on the vertical structure of the PBL in the NE Pacific.

While just over 14 years of PBLH observations from GNSS-RO or 18+ years of CTH observations from MISR are not adequate to infer potential characteristics about longer-term variability, we note that there are two enhanced periods of CTH', LR' and even ONI, suggestive of the PDO possibly at play in terms of describing a nearly one-decade wavelength. While higher frequency ENSO spectral modes are more prominent, a weaker, slower 8-10 year-mode also exists, and furthermore central Pacific ENSO variability may be operating at a slower 7-11-year spectral peak (Kim et al., 2012). That this sort of variability may be apparent in the satellite record warrants not only further investigation, but strongly argues for continuity of these cloud and PBL datasets into the future, and also implies the important consideration of slower time scales when analyzing longer satellite records (i.e. ISCCP). Finally, these modes offer a critical testbed for climate models, not just in terms their ability to simulate these climate indices with fidelity, but also the response of low cloud height and PBL height variability.

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Open Research

Data Availability

Analyzed data from this study are available from the JPL repository at https://genesis.jpl.nasa.gov/ftp/publication_data/Kubar_etal_JGR/. Data used to calculate MISR cloud top heights as described in the text are publicly available at https://doi.org/10.5067/Terra/MISR/MIL3MCFA_L3.001. Regional PBL heights as analyzed are available at the aforementioned repository. ERA5 SST and ω and temperature pressure-level data are available at https://doi.org/10.24381/cds.f17050d7 and https://doi.org/10.24381/cds.6860a573 and described by Hersbach et al. (2023a; 2023b). Analyses were performed and figures were generated using IDL (Interactive Data Language) software from L3Harris Geospatial software licensed for use by Jet Propulsion Laboratory. Links to ENSO and PDO data time series are described and provided in the main text.

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