

Patterns in Pre-PyroCb Meteorological Condition Changes: A Comparative Regional Study

1 Introduction

Pyrocumulonimbus (PyroCb) refers to the extreme dry thunderstorms triggered by intense surface heating by wildfires, which can generate strong updrafts and super efficient smoke chimney injecting wildfire emissions into upper troposphere and lower troposphere (UTLS). It has been confirmed by observations that the intense-PyroCb-conducted aerosol disruption to the stratosphere is comparative to moderate volcanic eruptions. However, three contrasts between volcanic eruptions and PyroCb should be noted. First, volcanic eruptions are considered as a natural forcing on the climate system while PyroCb events are related to increased wildfire activities that is partially attributed to anthropogenic climate change. Second, volcanoes erupt at a relatively low frequency while over 40 PyroCb events occur every year around the world. And there is a high probability that a lot more PyroCb have never been detected due to the spatial and temporal (especially lack of nighttime observation) limitation of satellite data or documented due to limited focus on collecting PyroCb records. Third, volcanic eruptions mainly inject reflective aerosols (sulfate aerosols) to the stratosphere, which has cooling effects. Conversely, PyroCb injects a considerable amount of organic carbon including black carbon (BC) and brown carbon (BrC) that absorb solar radiation and heat the stratosphere. A recent Science paper estimated that 10~25% of BC in the stratosphere over the past decade are from PyroCb source. There is also paper reporting that PyroCb can increase the temperature in local stratosphere by up to 9 K. What's more, PyroCb aerosols that have made it to the UTLS can rapidly spread across the globe and stay in the UTLS for a long time. For example, the stratospheric aerosol anomaly caused by 2017 Northeast Pacific PyroCb events was detectable for over 8 months. Thus, there is no denying that PyroCb can produce large-scale and prolonged climatic impacts. Other than being an increasingly important climate forcer under the background of enhanced wildfire activities, PyroCb is a deadly disaster for people nearby. During a PyroCb, the entrainment of dry air at base will further stokes the fire. The erratic wind fields can cause unpredictable wildfire spread. The lightning in the thunderstorm can ignite new fires far away. Hence, fire management agencies are trying hard to monitor PyroCb

behaviors to reduce life and property loss. However, it is still challenging to predict when and where PyroCb forms. Hence, understanding the development of PyroCb is critical for both climate projection and disaster loss reduction.

Current scientific understanding of PyroCb formation is still in the infancy although there is already some accumulation of insights gained from theoretical, simulational, statistical, observational, and machine-learning perspectives. Tory and Kepert, 2020 analytically solved Brigg's bulk plume model and gave the formula of the firepower threshold for PyroCb development under any given atmospheric profile. Although this work uses simplified assumptions including predefined ratio between moist and heat contributed by wildfire and constant wind field, the formula suggests that it requires more energy from the fire to overcome capping inversion and horizontal wind to raise the plume into UTLS. Tarshish and Romps, 2022 found that despite extreme sensible heating from wildfires, latent heat release through condensation is still necessary for PyroCb formation. Based on a community inventory of 26 intense pyroCb events in 2013 in western United States and Canada, a control dataset of intense fire activity without the development of pyroCb during the same wildfires as the pyroCb's, and reanalyzed meteorological model outputs, Peterson et al., 2017 summarised the meteorological condition differences between PyroCb events and intense wildfires that failed to induce pyroCb. This is the first conceptual model for intense pyrocumulonimbus (pyroCb) development. It reveals that it is not effective to tell whether a wildfire weather can evolve into pyroCb by applying dry, hot, and windy surface criteria that are popular in wildfire studies. Instead, lower and mid-troposphere instability, mid troposphere humidity, and upper troposphere dynamics may be factors that distinguish pyroCb from extreme wildfire weather without pyroCb. Also, this study pointed out that elevation of the wildfire surface can affect the meteorological requirements of pyroCb. Simulational studies tested the sensitivities of wildfire-generated smoke plume height on fire properties (e.g. geometry, burned area, firepower) and fuel properties (e.g., dryness, vegetation type, density), demonstrating the complexity of factors affecting pyroCb. Observational studies that intend to reveal the mechanism of pyroCb mainly adopted data from nearby weather radars which provides temporal resolution up to several minutes. Yet such studies were constrained to few sites and events. Recently, a machine learning team developed a machine learning pipeline called PYROCAST to forecast pyroCb in a given wildfire 6 hours in

advance based on geostationary images and environmental parameters for 148 PyroCb events in 111 wildfires between 2018 and 2022 spanning North America, Australia, and Russia. The best algorithm they tried out predicted pyroCb with an AUC of 0.90 ± 0.04 . This same team also developed a causal inference model to find the causes of pyroCb. However, the machine learning tool is like a black box with poor interpretability. And the causal model cannot take into account of the interactions between the fire and the weather, which damaged its reliability. Hence, there is still a pressing need to illuminate how pyroCb forms.

Here I leverage the pyrocb database shared by the PYROCAST team and ERA5 hourly reanalysis products to explore meteorological factors conducive to pyroCb by analyzing the pattern of changes in meteorological parameters over the several hours before pyroCb, which may contain the key period for pyroCb development. To my knowledge, this is the first study that looks into the the common pattern of meteorological condition's time series before a dataset of pyroCb events. Moreover, interregional comparison of the patterns are conducted to reveal potential regional differences.

2 Methods

This study incorporates an inventory collected by Tazi et al., 2022 consisting of 81 intense pyroCb events occurred in the U.S., Canada, Australia, and Russia in 2018~2022 detected by satellite GEOS and HIMAWARI (<https://spaceml.org/repo/project/63691212f97150000d504d4d>). This inventory includes the location (latitude and longitude) of pyroCb events and the time when pyroCb were detected using algorithm described in Peterson et al., 2017. ERA5 hourly and monthly averaged hourly data on pressure levels and single levels corresponding to each pyroCb event was downloaded using Copernicus Climate Data Store API (<https://cds.climate.copernicus.eu/cdsapp#!/search?type=dataset&text=ERA5>). The hourly data were used to derive the meteorological conditions during and before each pyroCb event. The monthly averaged data also provide hourly value despite aggregated monthly for each hour. They were used to derive the background meteorological conditions on normal days for hours relevant to each pyroCb event. The anomaly of each meteorological parameter was calculated by subtracting the monthly mean values (background) from the real time values. Wildfire surface elevations for each

pyroCb location were derived from NASA SRTM Digital Elevation 30m data product (https://developers.google.com/earth-engine/datasets/catalog/USGS_SRTMGL1_003) through Google Earth Engine. The processing of each meteorological parameters is stated in the following section. To examine the pattern of how meteorological factors change over pre-pyroCb hours, 5 time windows were chosen (2/3/4/5/6 hrs before pyroCb). Box plots were created to examine the distribution of values. 75% percentile, median, and 25% percentile are marked in the plots. Since the conclusions derived from these different time windows are similar, only the plots for 4 hrs before pyroCb are shown in the main text. For complete datasets, codes, and plots, please visit the author's github page <https://github.com/ChloeYangfan>.

3 Results and discussions

3.1 Lower Troposphere Conditions

The concept of lower troposphere here refers to the atmosphere between the upper boundary of the mixed layer (boundary layer) and the cloud base height. The reason why I excluded the boundary layer is that the atmospheric conditions in this layer are highly variable and depends on the complex surface properties. The discussion starts with this layer without mentioning surface meteorological conditions because Peterson et al., 2017 has shown the inefficacy of surface weather conditions in predicting pyroCb in an intense fire.

3.1.1 Lower Troposphere Instability

To quantify the lower troposphere instability, I calculated the mean temperature lapse rate in this layer (LTLR), a metric retained from Peterson et al., 2017. The more negative LTLR is, the more unstable the lower troposphere is. According to Fig 1, LTLR decreased over the 2-6 hour pre-pyroCb windows for the vast majority of pyroCb events in the inventory adopted by this study. However, it is noteworthy that such enhancement in low-level atmospheric instability is mainly attributable to the background trend. Actually, most of the pyroCb events occur in the local afternoon when atmospheric instability reaches its peak. Thus, it is no suprising that lower troposphere instability increases before most pyroCb events. However, it is interesting that before most pyroCb events, the lower troposphere instability enhances less than it does on a normal day. I guess it may imply that the threshold of lower troposphere instability for pyroCb development is usually easy to reach. And some other

conditions that boosts pyroCb development may hinder the accumulation of lower troposphere instability during pre-pyroCb hours.

3.2.1 Vertical Wind Shear

Peterson et al., 2017 found that North-American pyroCb weathers have relatively small low-level vertical wind shears, which makes it easier for smoke plume to rise. Then a natural question follows: is pre-pyroCb weather accompanied by reduction in vertical wind shear? In order to answer this question, I used the mean vertical wind speed difference between adjacent pressure levels in the lower troposphere (LTVWS_speed_diff_mean) to quantify low-level vertical wind shear and examined its change before pyroCb. Results are shown in Fig. 2.

It turns out that vertical wind shear significantly diminished before pyroCb at all elevations in contiguous US. But the major contributor to this diminishment varies with elevations. For low elevations (<1km) and high elevations (>2km), pre-pyroCb weather anomalies are the major contributors. For mid elevations (1~2km), background trend made the primary contribution.

For low elevations (<1km) in Canada and Alaska, the change in vertical wind shear is small as the background trend is positive ($\Delta\text{LTVWS_speed_diff_mean_bg} > 0$) yet the pre-pyroCb anomalous trend is negative ($\Delta\text{LTVWS_speed_diff_mean_anomaly} < 0$). They largely canceled with each other. However, for the mid elevations (1~2km) in Canada and Alaska, although $\Delta\text{LTVWS_speed_diff_mean_bg}$ is positive, $\Delta\text{LTVWS_speed_diff_mean_anomaly}$ is so negative that the net change in vertical wind shear several hours before is significantly negative. This suggests that there will be abnormal significant reduction in lower troposphere vertical wind shear in mid elevations of Canada and Alaska before pyroCb, which reverses the background trend of this meteorological parameter over the course of the day. This may be informative for pyroCb forecast in these regions. I suggest future studies check this with mechanistic models. As for low elevations (<1km) in Australia, things are similar to mid elevations in Canada and Alaska, which deserves further study.

By contrast with the phenomena in North America and Australia, the lower troposphere vertical wind shear strengthened before low-elevation (<1km) Russian pyroCb events. It is counterintuitive as stronger low-level vertical wind shear inhibits smoke plume to rise. This implies there must be other favorable conditions for these

pyroCb events to overcome such disadvantage or vertical wind shear is never a limiting factor for plume rise in this region.

3.2 Mid Troposphere Conditions

The lower boundary of mid troposphere in this study was defined as the mean cloud base height of the pyroCb location in the month pyroCb occurred. Usually the corresponding pressure level ranges from 800 hPa to 700 hPa. The upper boundary of mid troposphere was chosen according to Peterson et al., 2017 as the pressure level that is roughly right behind the upper tropospheric dynamic features like jet streams. For Australia and Contiguous United States, it was defined as 300 hPa. For Russia, Canada, and Alaska, it was defined as 400 hPa.

3.2.1 Mid Troposphere Moisture

The moisture in mid troposphere is represented by mean relative humidity within this layer (MTRH). Peterson et al., 2017 found that for western US and Canadian, mid troposphere is moister in pyroCb than in extreme wildfires without pyroCb. Consequently, they argue that it is important for pyroCb formation in these regions. Here we can observe that for both low-elevation (<1km) and high-elevation (>2km) pyroCb events in the contiguous US, for both low-elevation (<1km) and mid-elevation (1~2km) pyroCb events in Canada and Alaska, mid troposphere moist increases over the last several hours before pyroCb (see Fig. 3). Such increase can be attributed to both the background trend and the anomalies of pre-pyroCb weathers. And it suggests that moist will accumulate in the mid troposphere with a higher rate than normal during the course of the day before pyroCb events in these regions.

As for Australia, there exists controversy over whether mid level moist is required for pyroCb to occur. According to the statistics here, the changes in MTRH before pyroCb events are almost half positive and half negative. So the role of mid troposphere moist remains unclear. The case is similar for Russia.

3.2.2 Mid Troposphere Potential Instability

Mid troposphere potential instability was represented by the mean lapse rate of equivalent potential temperature in the mid troposphere (MTPI), a metric that is similar to PI in Peterson et al., 2017. As in a stable mid troposphere, equivalent temperature increases with height. The higher its lapse rate, the stabler the mid troposphere. Hence, the potential instability in mid troposphere increases if the metric

MTPI decreases. It can be easily deduced that if $\Delta\text{MTPI} < 0$, it means that the atmospheric condition becomes more and more favorable for pyroCb development over time.

As expected, it can be seen from the box plots (see Fig. 4) that for the majority of low-elevation ($<1\text{km}$) pyroCb events in contiguous US, Canada and Alaska, and Russia. MTPI decreased ($\Delta\text{MTPI} < 0$) over the several-hour time windows before pyroCb, which means mid troposphere become more unstable in these locations before pyroCb develops. What's more, MTPI_anomaly also decreased ($\Delta\text{MTPI_anomaly} < 0$) for these events, which means after removing the background trend, there is still enhancement in mid troposphere instability. It further suggests that during wildfire weathers when pyroCb will occur in a few hours, mid troposphere potential instability will be enhancing with higher rate than during the same course on normal days. For mid- ($1\sim2\text{km}$) elevation pyroCb events in Canada, as $\Delta\text{MTPI_anomaly}$ approach zero, the decrease in MTPI is mainly caused by background trend. So there is no obvious deviation from normal with respect to mid troposphere potential instability for these events.

What's counterintuitive is that, in low-elevation ($<1\text{km}$) surfaces in Australia, despite the MTPI should decrease during the course of the day on normal days ($\Delta\text{MTPI_bg} < 0$), before pyroCb occurs, it anomalously increases ($\Delta\text{MTPI} > 0$, $\Delta\text{MTPI_anomaly} > 0$). This is surprising because it suggests that mid troposphere becomes stabler before pyroCb outbursts. So low-elevation ($<1\text{km}$) pyroCb development in Australia will have to overcome such unfavorable mid troposphere conditions.

3.3 Upper Troposphere Conditions

Peterson et al., 2017 points out that there exists weak upper troposphere divergence for most pyroCb events in 2013 in North America whereas for intense wildfires that failed to develop pyroCb, there is convergence at upper level. As upper level divergence promotes air to rise, it is obviously an advantage for pyroCb development. Variable 'd' or 'upper troposphere divergence' at predefined level in the ERA5 data on pressure levels were directly used to represent upper troposphere divergence (utd). Here the pressure levels to extract upper troposphere dynamics were defined as 250 hPa for Contiguous US and Australia while 300 hPa for Canada, Alaska, and Russia considering their diversities in tropopause pressure levels and reference values in

Peterson et al., 2017. It can be seen from Fig. 5 that for most pyroCb events occurred at mid elevations (1~2 km) in contiguous US, there is increase in upper level divergence over the 4 hrs before pyroCb. Furthermore, because the background change is almost half positive and half negative while the pre-pyroCb anomaly changes are consistently positive, the increasing upper troposphere divergence mainly emanates from the pre-pyroCb anomalous weather. For most low elevation (< 1km) pyroCb events in contiguous US and Russia, counterintuitively, upper troposphere divergence fell over the pre-pyroCb period. Besides, change of pre-pyroCb upper troposphere anomalies for most of these events are negative, indicating that on these pyroCb days upper troposphere divergence decreased more than normal during the course of the day which is several hours before pyroCb occurred. For other events including low (< 1km) and mid (1~2 km) elevation events in Canada and Alaska, low elevation (< 1km) events in Australia, and high elevation events (>2km) in contiguous US, there is no clear common pattern in the change of upper troposphere divergence before pyroCb.

4 Conclusions

This study looked into the common patterns of pre-pyroCb temporal evolution over the timescale of several hours of meteorological factors in lower, mid, and upper troposphere that have been recognized as potentially important for pyroCb development in existing literature, including lower troposphere instability, lower troposphere vertical wind shear, mid troposphere potential instability, mid troposphere moisture, and upper troposphere divergence. Differences among different regions including contiguous US, Canada and Alaska, Australia, and Russia were presented. Wildfire surface elevation variations were also discussed. The anomalous pre-pyroCb patterns that are in sharp contrast with background trends found by this study (e.g. dramatic lower troposphere vertical wind shear reduction that reverses the background trend of enhanced wind shear) may be the key to unravel the mechanism of pyroCb development thus deserving further studies.

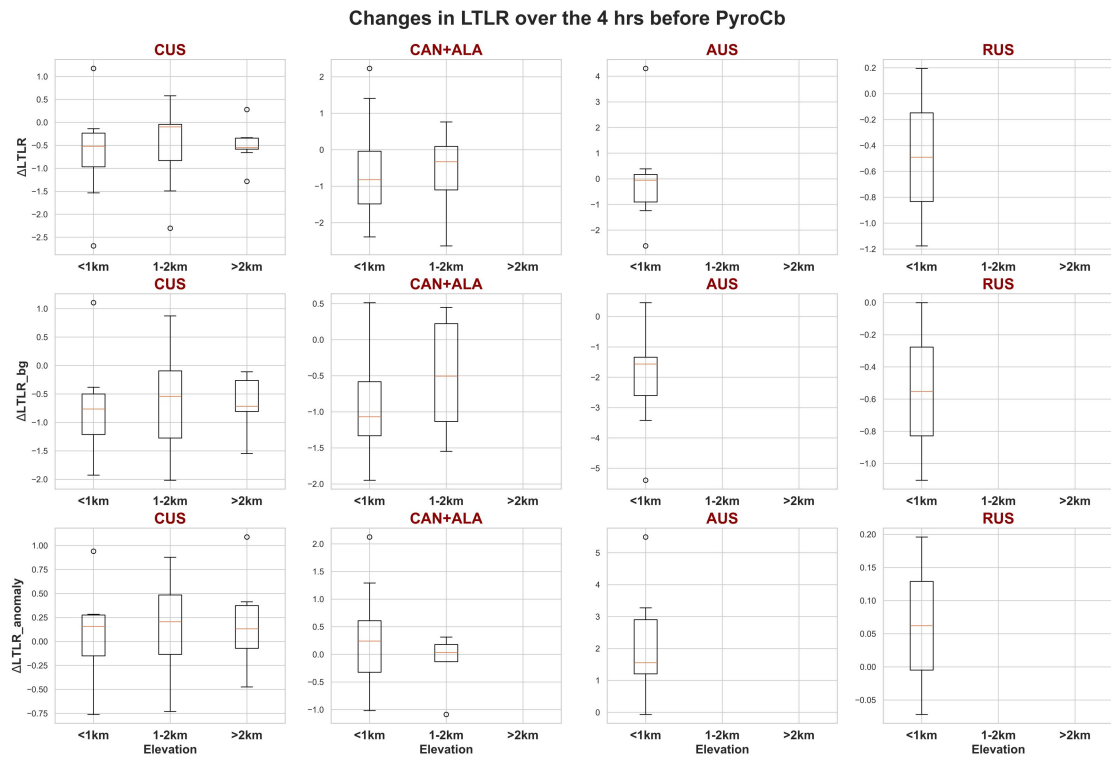


Fig 1. Changes in lower troposphere instability over the 4 hours before pyroCb.

Note that lower LTLR indicates higher instability. If $\Delta\text{LTLR} < 0$, the lower troposphere becomes more unstable over time. Each column represents a different region. (CUS for contiguous US, CAN+ALA for Canada and Alaska, AUS for Australia, RUS for Russia). The top row is for the changes in LTLR on the day of pyroCb. The middle row is for background LTLR change, which refers to changes in LTLR during the same course of the day as pyroCb events on normal days. The bottom row is for the changes in LTLR anomaly relative to the background on the day of pyroCb. Basically, the data used to plot the bottom row are derived by subtracting the corresponding data in the middle from that in the top row. Blank space suggests there was no data in such category or certain parameters required for the calculation of LTLR were missing.

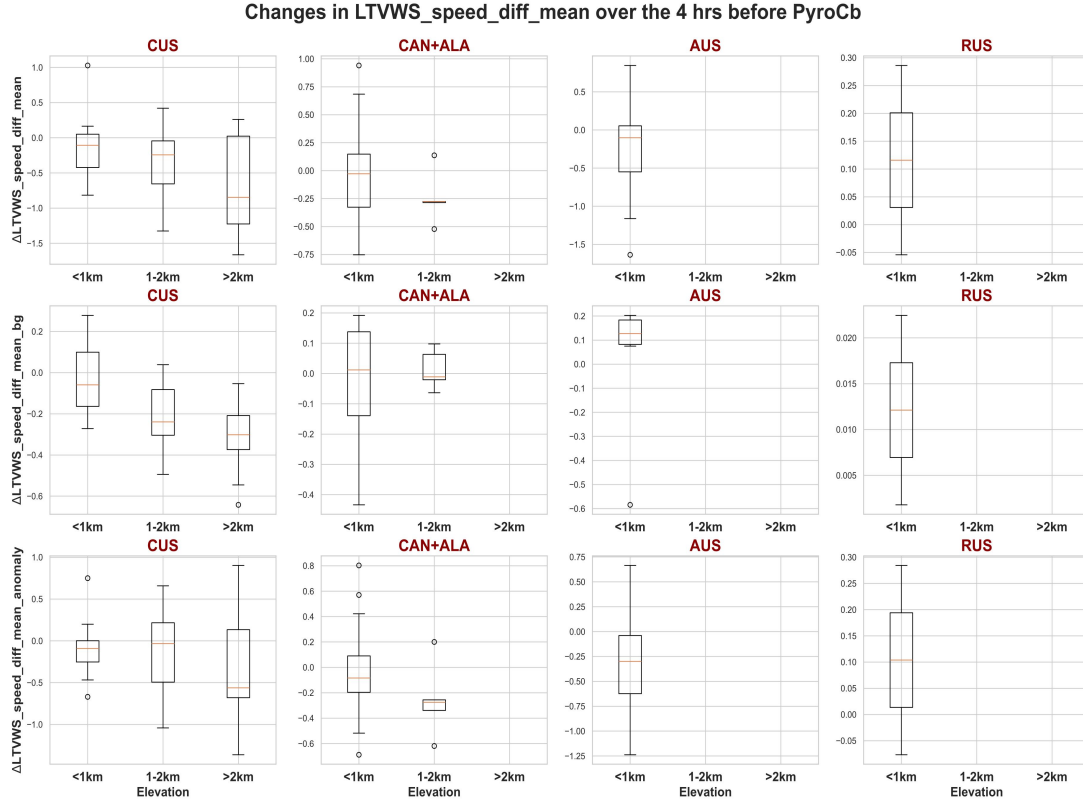


Fig 2. Changes in lower troposphere vertical wind shear over the 4 hours before pyroCb. Note that lower LTVWS_speed_diff_mean signifies lower vertical wind shear. If $\Delta\text{LTVWS_speed_diff_mean} < 0$, the lower troposphere becomes more favorable for smoke plume to rise over time. Each column represents a different region. (CUS for contiguous US, CAN+ALA for Canada and Alaska, AUS for Australia, RUS for Russia). The top row is for the changes in LTVWS_speed_diff_mean on the day of pyroCb. The middle row is for background LTVWS_speed_diff_mean change, which refers to changes in LTVWS_speed_diff_mean during the same course of the day as pyroCb events on normal days. The bottom row is for the changes in LTVWS_speed_diff_mean anomaly relative to the background on the day of pyroCb. Basically, the data used to plot the bottom row are derived by subtracting the corresponding data in the middle from that in the top row. Blank space suggests there was no data in such category or certain parameters required for the calculation of LTVWS_speed_diff_mean were missing.

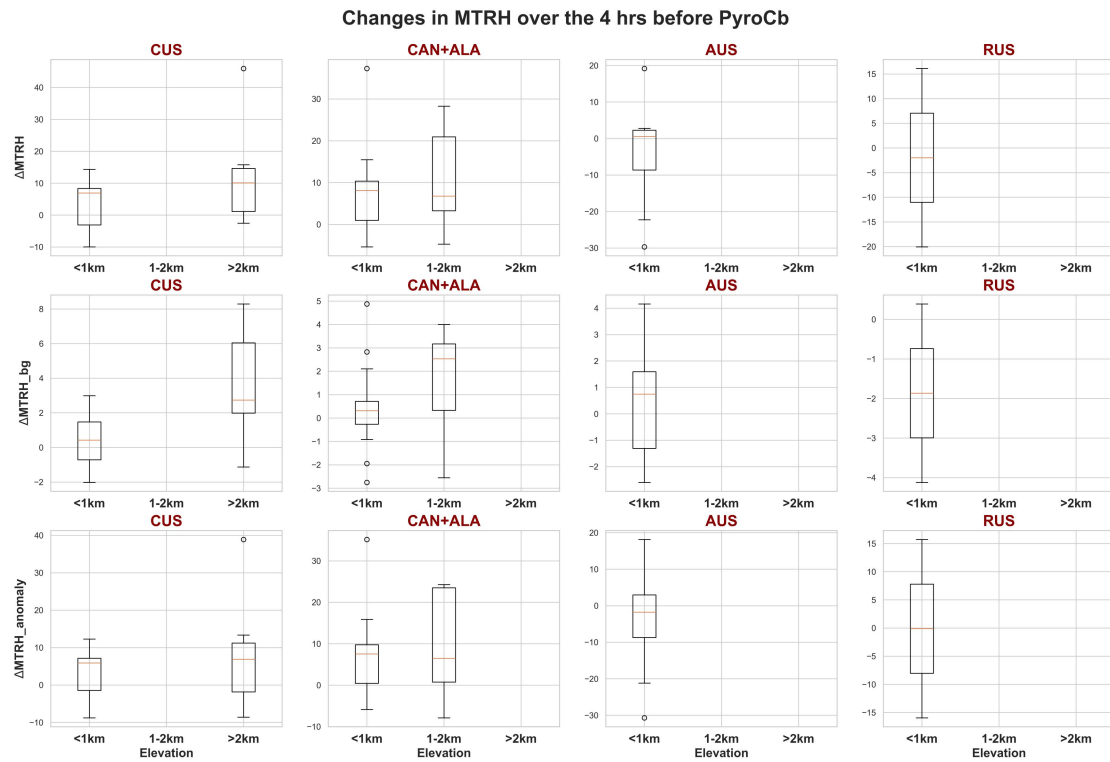


Fig 3. Changes in mid troposphere relative humidity over the 4 hours before pyroCb. Note that higher MTRH generally signifies more moist in the mid troposphere. If $\Delta\text{MTRH} > 0$, the mid troposphere becomes moister over time. Each column represents a different region. (CUS for contiguous US, CAN+ALA for Canada and Alaska, AUS for Australia, RUS for Russia). The top row is for the changes in MTRH on the day of pyroCb. The middle row is for background MTRH change, which refers to changes in MTRH during the same course of the day as pyroCb events on normal days. The bottom row is for the changes in MTRH anomaly relative to the background on the day of pyroCb. Basically, the data used to plot the bottom row are derived by subtracting the corresponding data in the middle from that in the top row. Blank space suggests there was no data in such category or certain parameters required for the calculation of MTRH were missing.

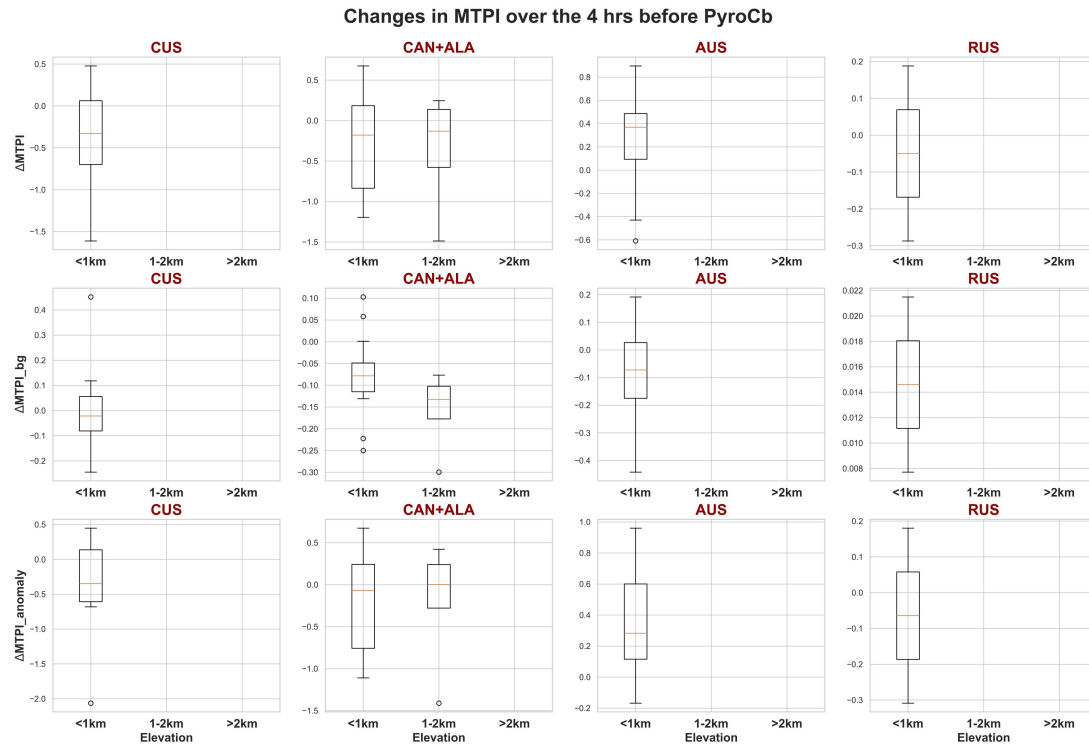


Fig 4. Changes in mid troposphere potential instability over the 4 hours before pyroCb. Note that lower MTPI signifies higher potential instability. If $\Delta\text{MTPI} < 0$, the mid troposphere becomes unstabler over time. Each column represents a different region. (CUS for contiguous US, CAN+ALA for Canada and Alaska, AUS for Australia, RUS for Russia). The top row is for the changes in MTPI on the day of pyroCb. The middle row is for background MTPI change, which refers to changes in MTPI during the same course of the day as pyroCb events on normal days. The bottom row is for the changes in MTPI anomaly relative to the background on the day of pyroCb. Basically, the data used to plot the bottom row are derived by subtracting the corresponding data in the middle from that in the top row. Blank space suggests there was no data in such category or certain parameters required for the calculation of MTPI were missing.

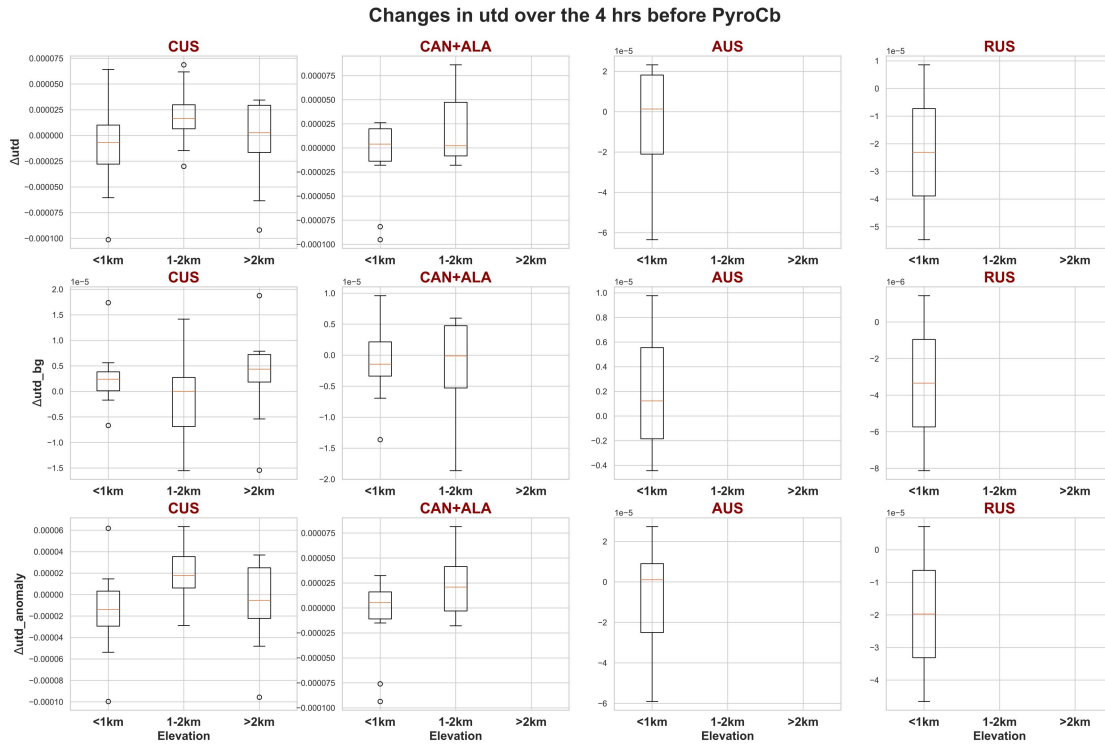


Fig 5. Changes in upper troposphere divergence over the 4 hours before pyroCb.

Note that lower MTPI signifies higher potential instability. If $\Delta\text{MTPI} < 0$, the mid troposphere becomes unstabler over time. Each column represents a different region. (CUS for contiguous US, CAN+ALA for Canada and Alaska, AUS for Australia, RUS for Russia). The top row is for the changes in MTPI on the day of pyroCb. The middle row is for background MTPI change, which refers to changes in MTPI during the same course of the day as pyroCb events on normal days. The bottom row is for the changes in MTPI anomaly relative to the background on the day of pyroCb. Basically, the data used to plot the bottom row are derived by subtracting the corresponding data in the middle from that in the top row. Blank space suggests there was no data in such category or certain parameters required for the calculation of MTPI were missing.

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