Climatology of Clear-Air Turbulence using the ERA5 data

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Turbulence Mitigation Workshop IV (Virtual), Nov. 9, 2021

Introduction

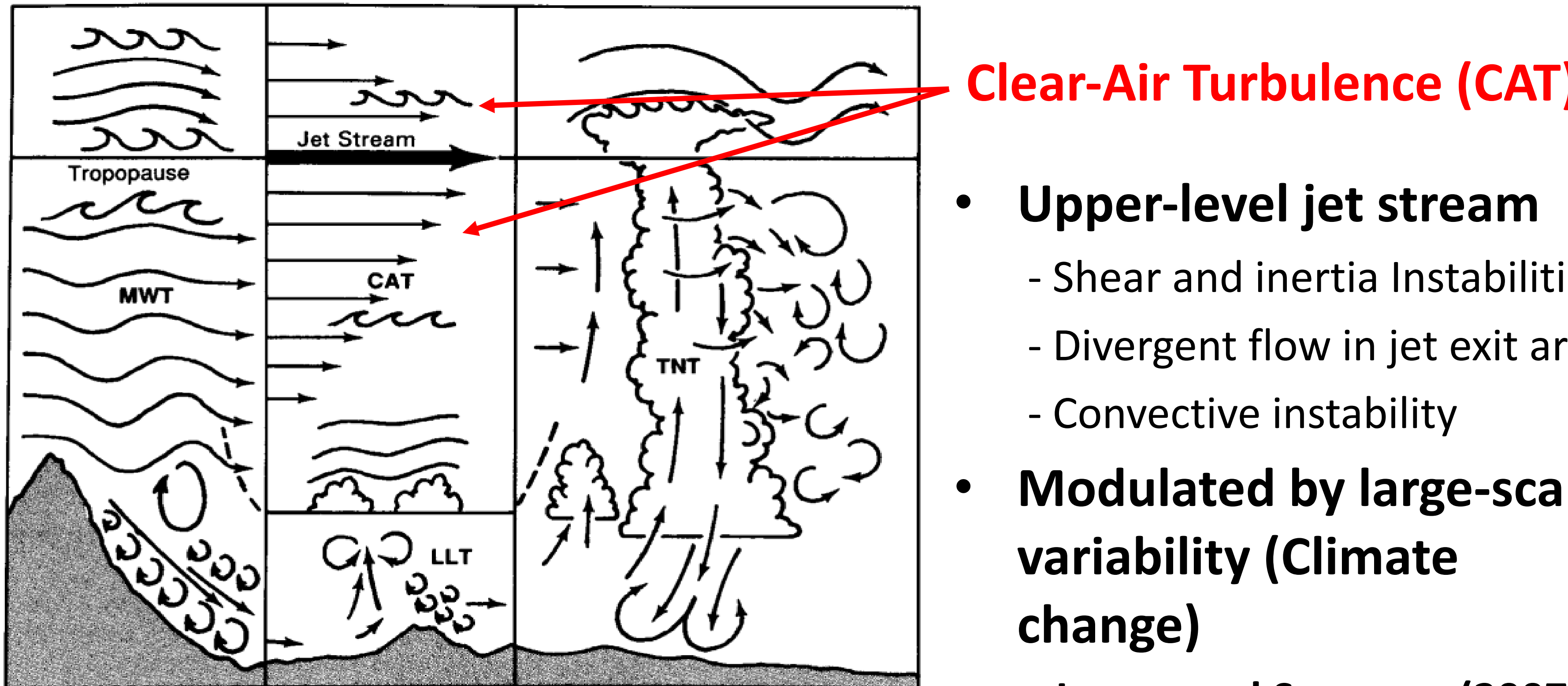


Figure 1-16. Aviation turbulence classifications. This figure is a pictorial summary of the turbulence-producing phenomena that may occur in each turbulence classification.

- **Upper-level jet stream**
  - Shear and inertia Instabilities
  - Divergent flow in jet exit area
  - Convective instability
- **Modulated by large-scale variability (Climate change)**
  - **Jaeger and Sprenger (2007):** CAT Climatology in ERA-40
  - **Lee et al. (2019):** VWS trend via thermal wind relation in the north Atlantic region using multiple reanalysis data

Aims of the current study:

1. Higher resolution of reanalysis data
2. CAT climatology of multiple sources
3. Long-term trends in multiple regions in NH

Data and CAT diagnostics

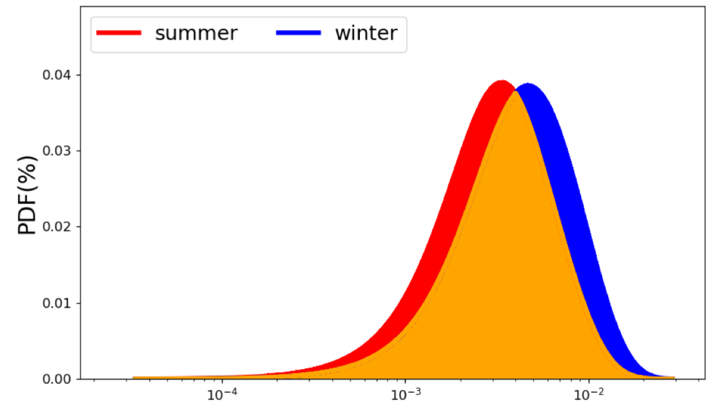
ERA5 (ECMWF ReAnalysis 5)	
Time resolution	· 6 hourly (00, 06, 12, 18 UTC) · From January 1979 to December 2019 **(41 years)**
Horizontal resolution	· **0.25° x 0.25°** grid spacing
Vertical resolution	· 12 levels (100, 125, 150, 175, 200, 225, 250, 300, 350, 400, 450, 500 hPa)

- **Turbulence Index version 1, 2, 3** (TI1, TI2, TI3) and their components [**vertical wind shear** (VWS), **deformation** (DEF), **-divergence** (-DIV), **divergence trend** (DVT)], which are widely used for diagnosing the CAT caused by shear instability and emission of inertia gravity waves near upper-level jet system.
- **Richardson number** (Ri), **squared Brunt-Väisälä** (N^2) and **Potential Vorticity** (PV) were also used to consider Kelvin-Helmholtz, hydrostatic and symmetric instability respectively.

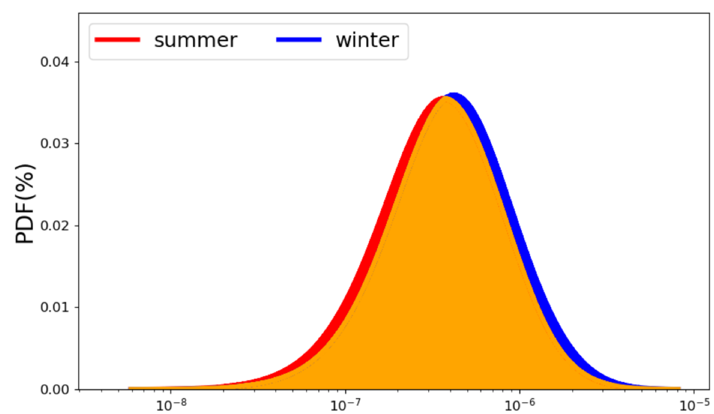
CAT thresholds in ERA5

- Values of top 5% (95th percentile) from **probability density function** (**PDF**) of each diagnostic for 41 years at 250hPa in the midlatitude region (20˚-60˚N) are considered as the thresholds for **Moderate or Greater** (**MOG**)-level CAT.

CAT Index	Threshold	Unit
VWS	$> 1.03 \times 10^{-2}$	s^{-1}
DEF	$> 1.29 \times 10^{-4}$	s^{-1}
-DIV	$> 5.15 \times 10^{-5}$	s^{-1}
DVT	$> 7.18 \times 10^{-5}$	s^{-1}
TI1	$> 9.07 \times 10^{-7}$	s^{-1}
TI2	$> 1.03 \times 10^{-6}$	s^{-1}
TI3	$> 1.39 \times 10^{-6}$	s^{-1}
N^2	< 0	s^{-2}
PV	< 0	1 PVU
Ri	$0 < Ri < 1$	-

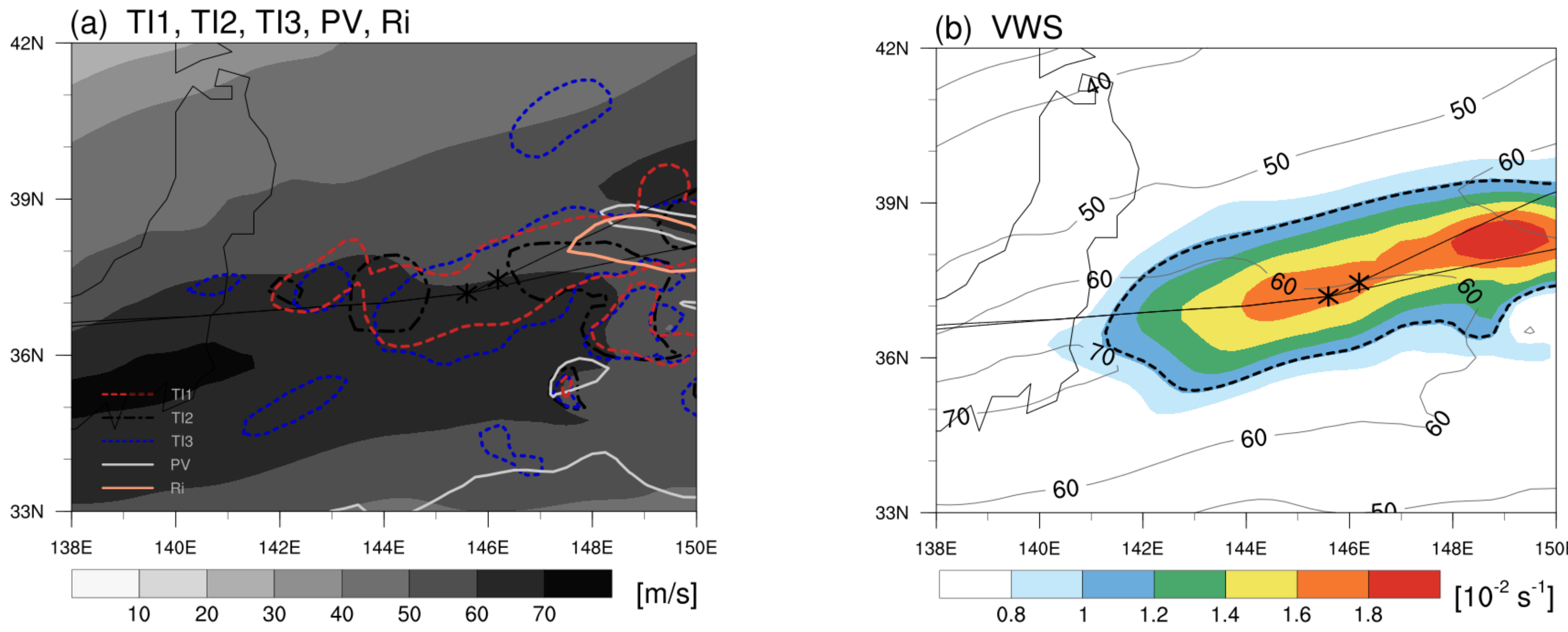


(a) VWS



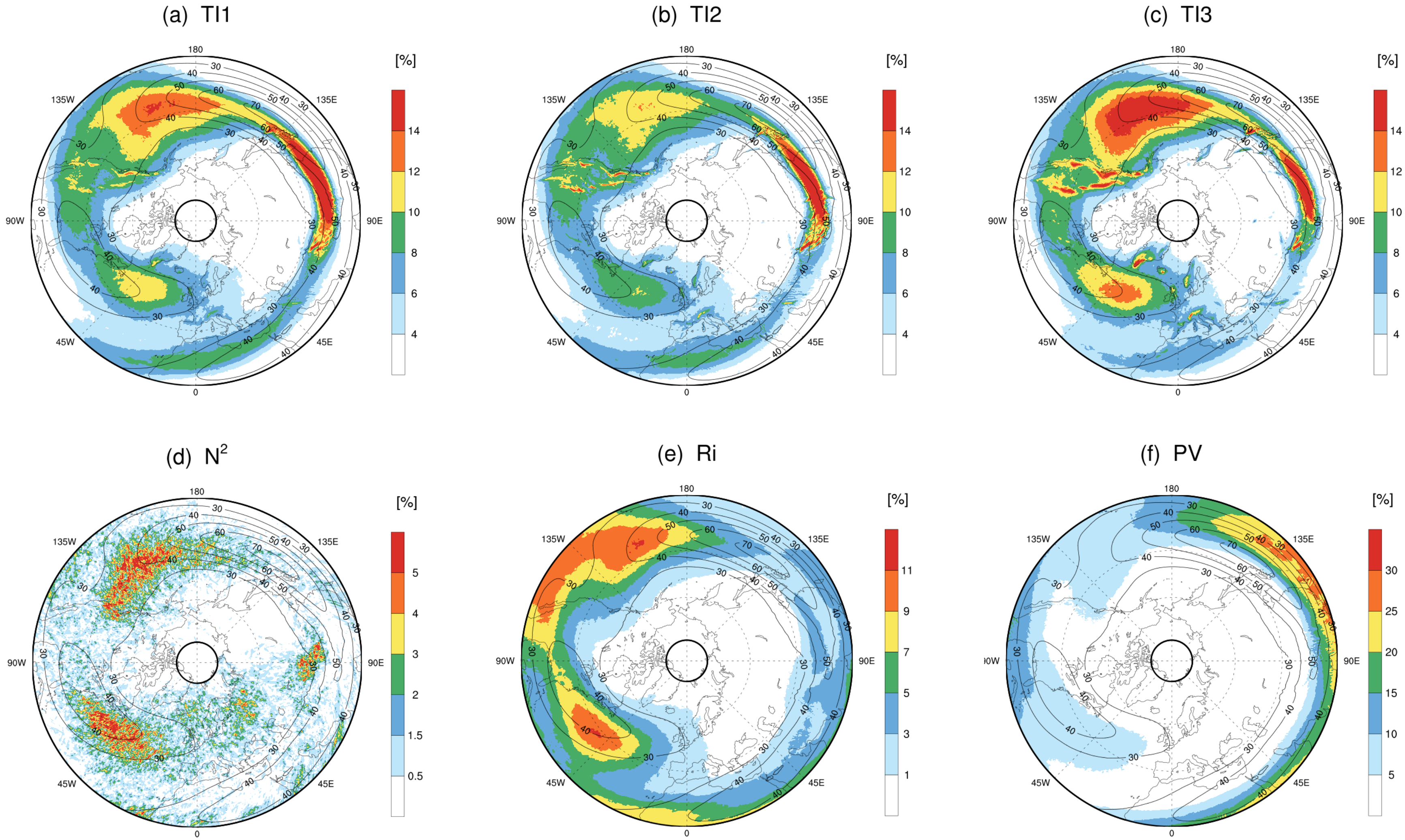
(g) TI3

CAT case study



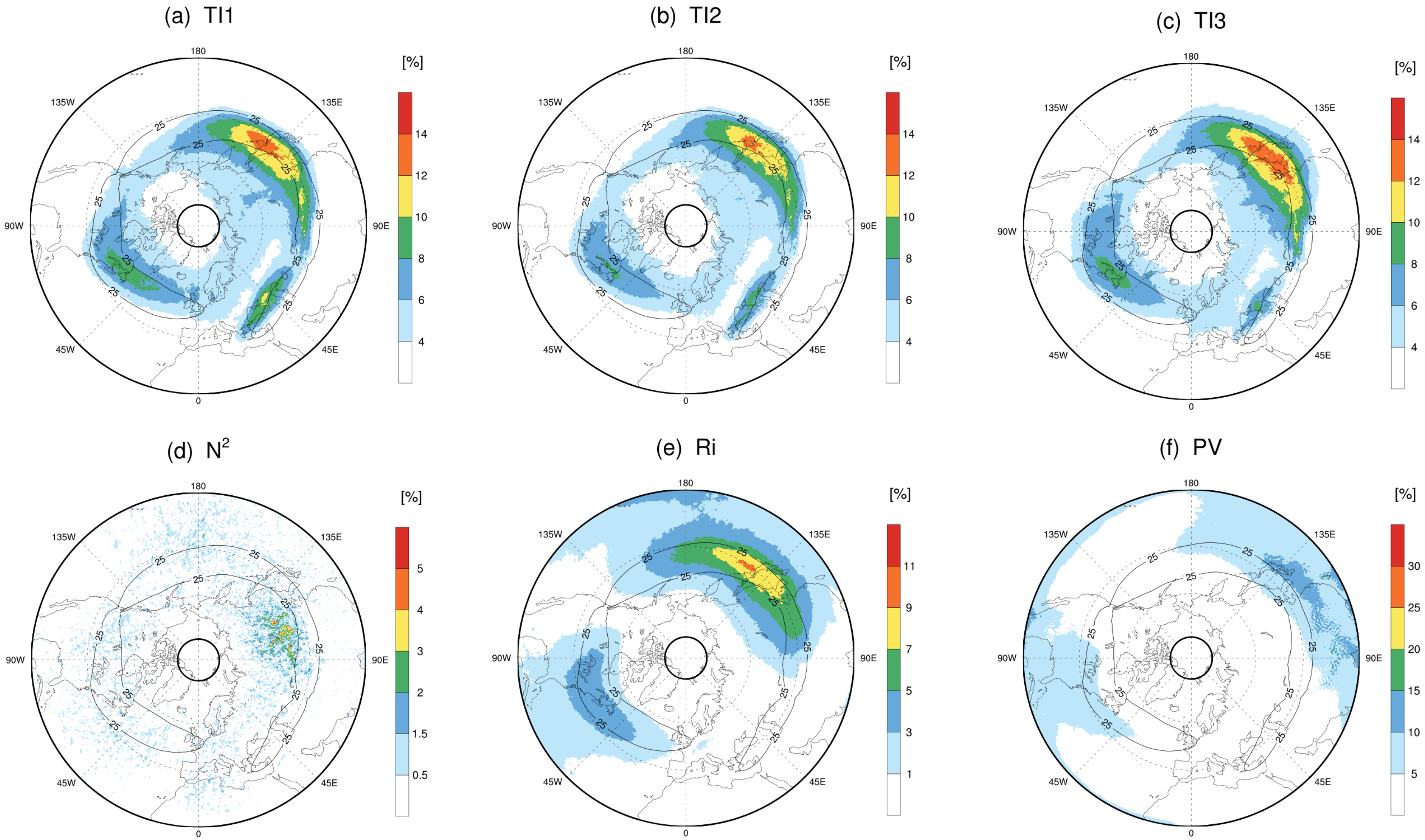
- At 1010 UTC and 1125 UTC October 2012, two flights encountered MOG-level CAT at about 11km in the Northwestern Pacific Ocean (eastern Japan).
- Shear (Kelvin-Helmholtz) instability with Ri < 1 occurred near these events (no convective instability: $N^2 > 0$) due to very strong VWS, resulted in very high values (top 5% thresholds) of TI1, TI2, and TI3 in this area.

Horizontal CAT climatology in NH



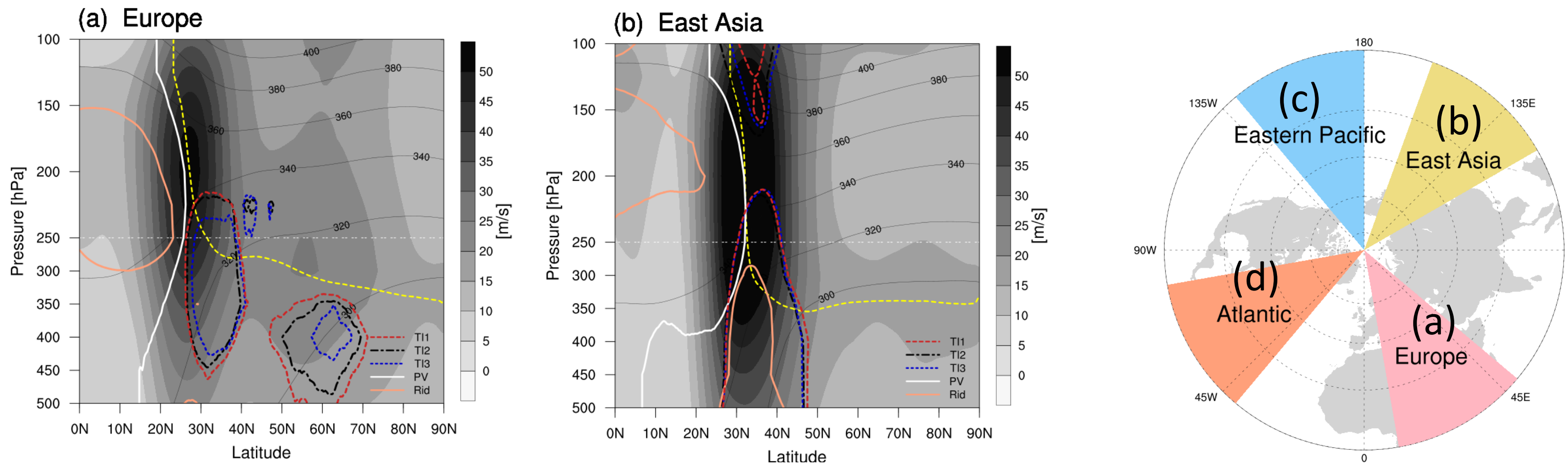
- Three (East Asia, Eastern Pacific and North Atlantic) regions of higher CAT occurrence are strongly associated with upper-level jet streams in winter in NH.

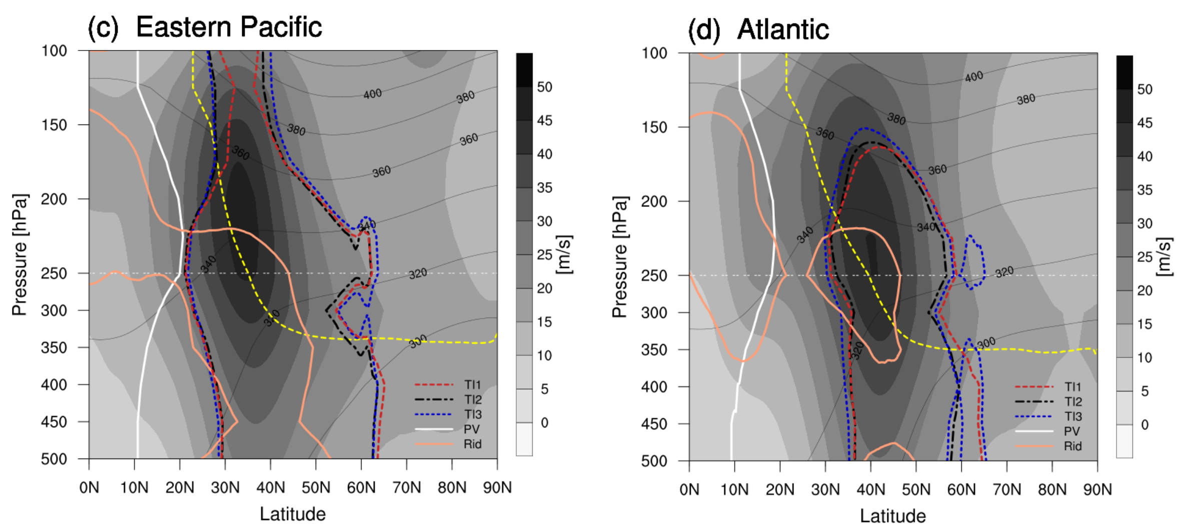
Horizontal CAT climatology in NH



- Patterns of higher CAT occurrence are shifted to northward in summer time due to the north shift and weak intensity of upper-level jet streams in NH.

Vertical CAT climatology in NH



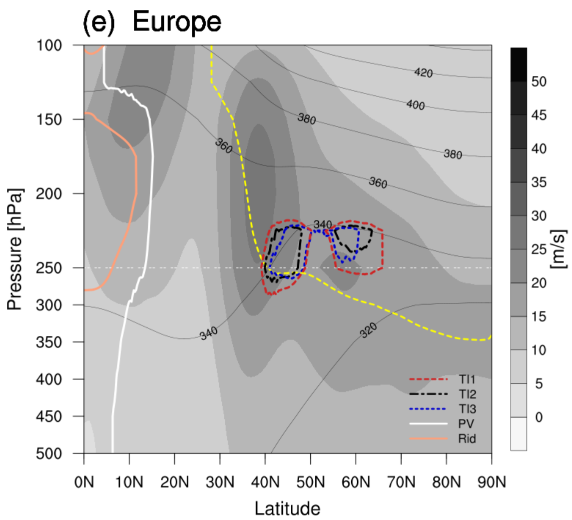


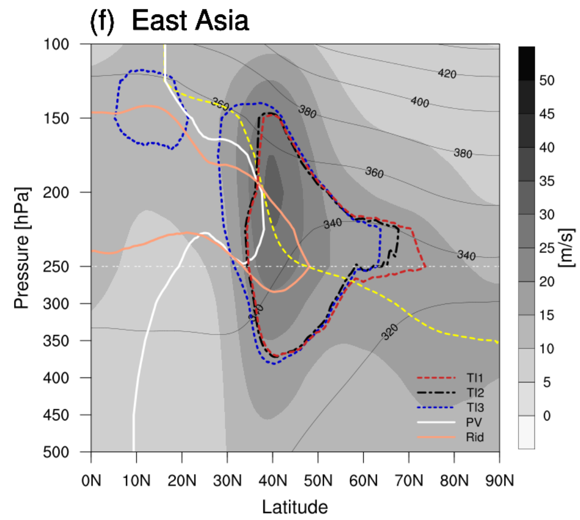
- (a) Europe: Two jet streams
- (b) East Asia: Jet entrance
- (c) Eastern Pacific and (d) Atlantic regions: Jet exit

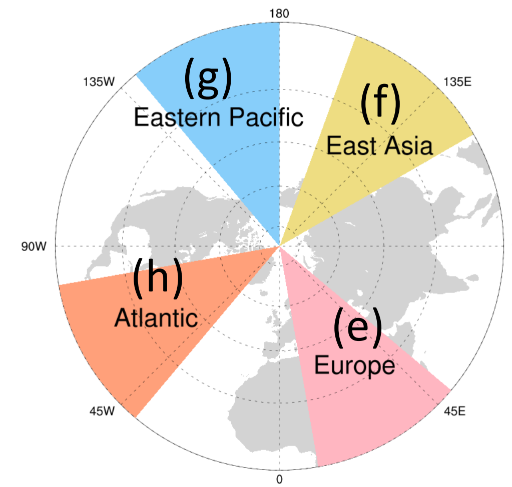
- Higher TI 1-3 at bottom and north side of jet core
- Higher Ri and PV in anti-cyclonic side of jet core

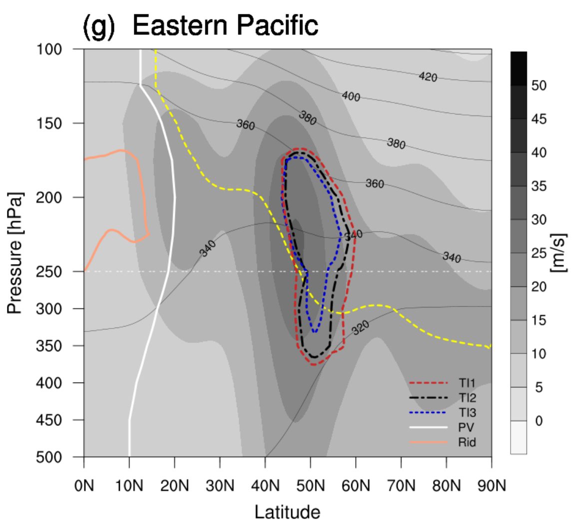
- Vertical distributions of CAT frequency for **TI1** (red dashed), **TI2** (black dashed), **TI3** (blue dotted), **PV** (white solid), Ri (pink solid) with shadings of zonal wind speed (**upper-level jet stream**) in winter for (a) Europe, (b) East Asia, (c) Eastern Pacific and (d) Atlantic regions.

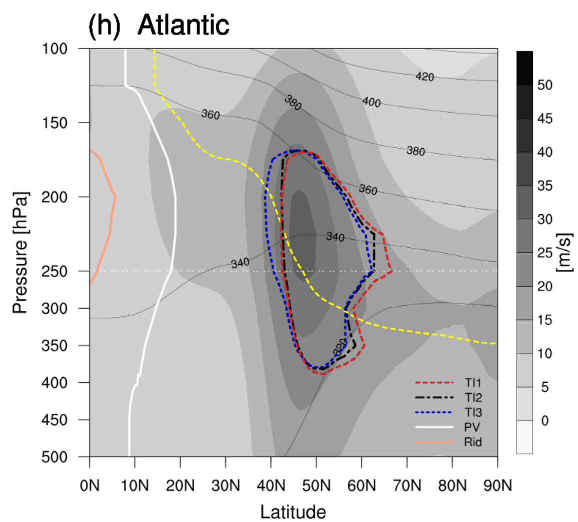
Vertical CAT climatology in NH









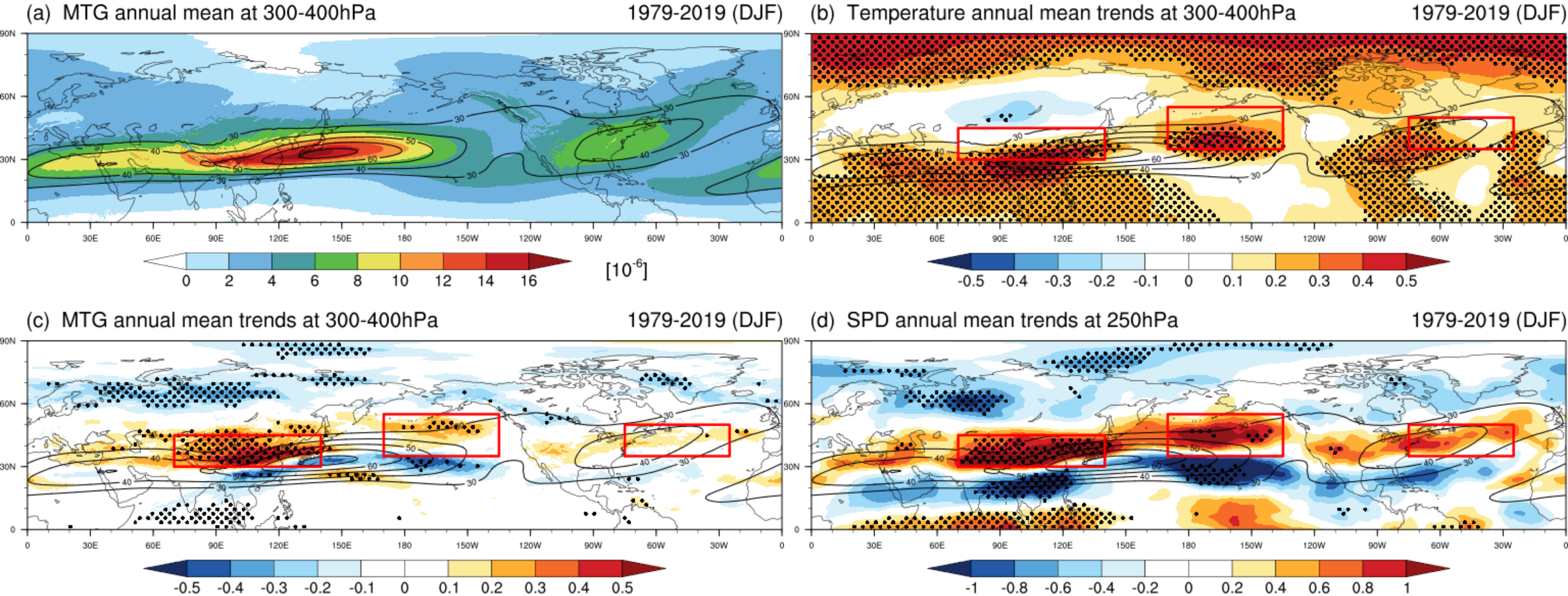


- (e) Europe: Two jet streams
- (f) East Asia: Jet entrance
- (g) Eastern Pacific and (h) Atlantic regions: Jet exit

- Jet becomes weaken and moves northward.
- Higher TI 1-3 is shifted and shrunken at higher altitudes.

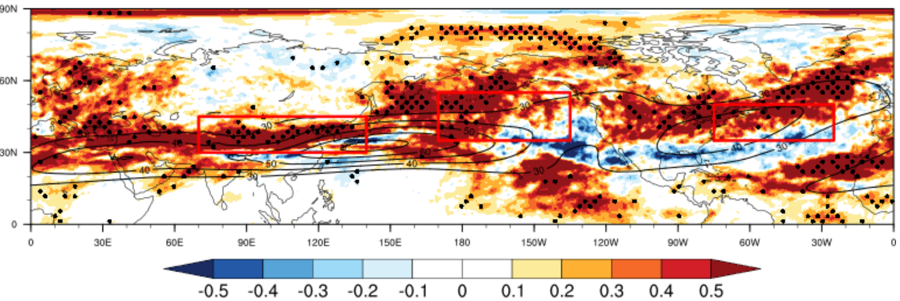
- Vertical distributions of CAT frequency for **TI1** (red dashed), **TI2** (black dashed), **TI3** (blue dotted), **PV** (white solid), Ri (pink solid) with shadings of zonal wind speed (**upper-level jet stream**) in summer for (a) Europe, (b) East Asia, (c) Eastern Pacific and (d) Atlantic regions.

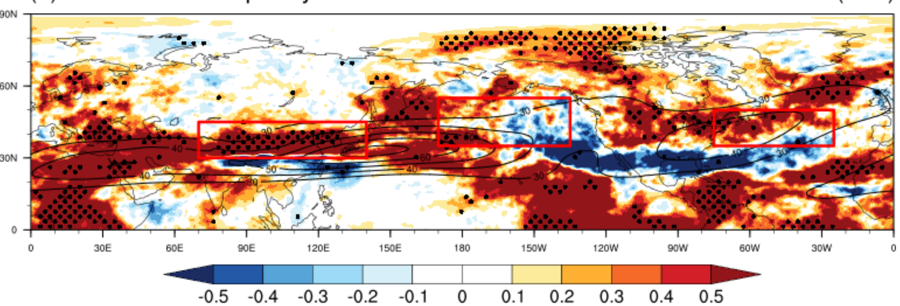
Long-term trend in CAT climatology

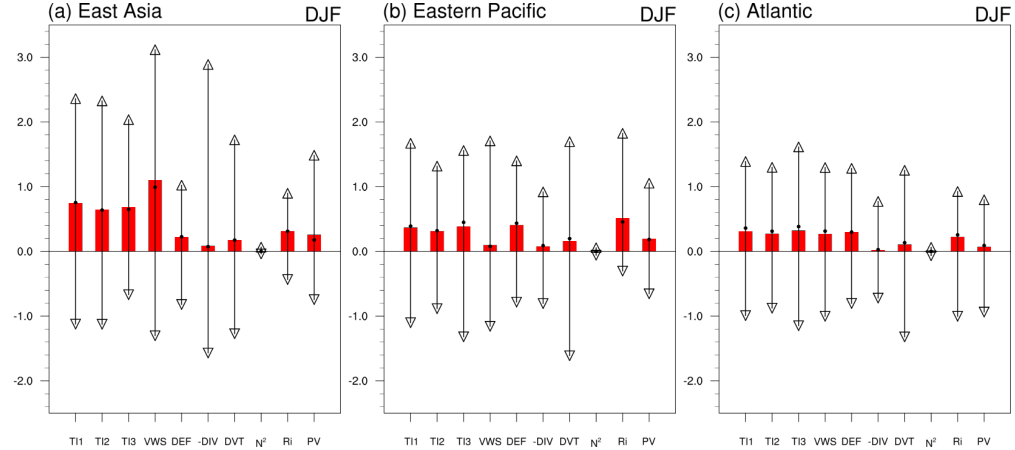


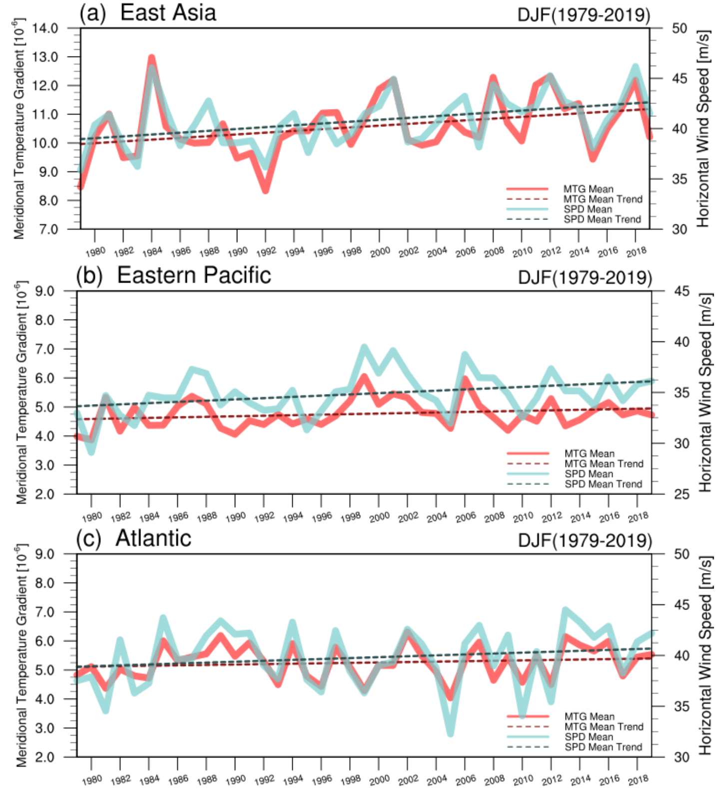
- (a) Annual mean of Meridional Temperature Gradient (MTG: shading) at 300-400hPa
- (b) Annual mean trends of temperature (shading) at 300-400hPa
- (c) Annual mean trends of Meridional Temperature Gradient (shading) at 300-400hPa
- (d) Annual mean trends of zonal wind speed at 250hPa
- Significant increasements are depicted by black dots. (p-value < 0.05, $n = 41$).
- **Increasements in MTG (c) → Stronger upper-level jet stream (red boxes in d)**
  in East Asia, Eastern Pacific, and Northern Atlantic.

Long-term trend in CAT climatology



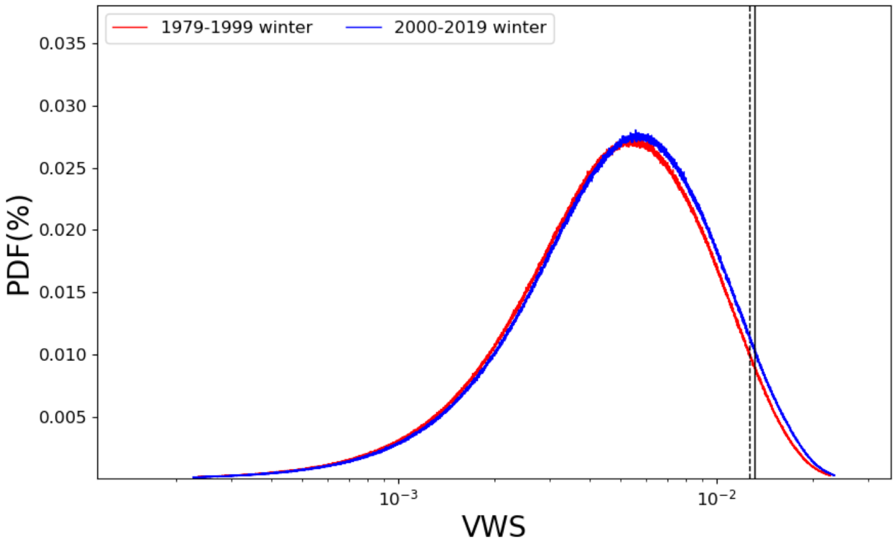


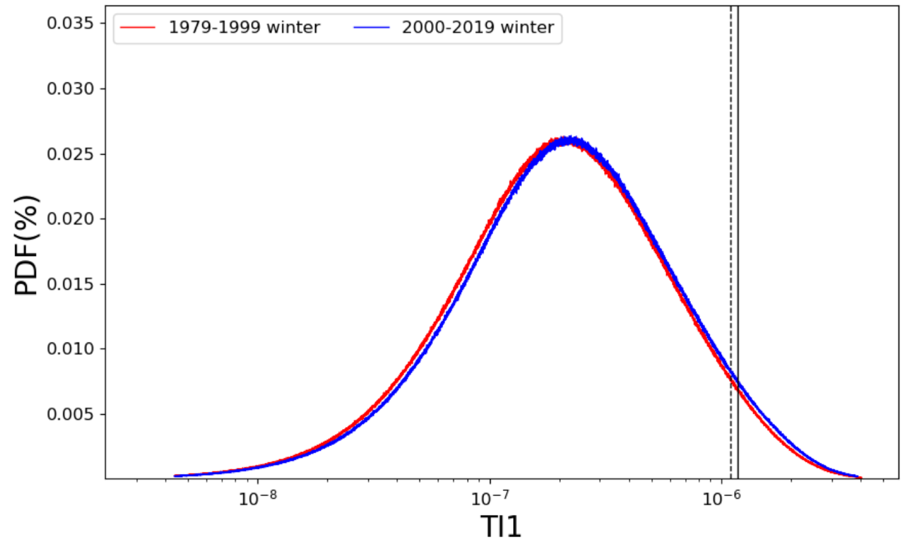




- Upper-left: Annual mean trends of (a) TI1 and (e) VWS for 41years on DJF. Significant increasements are depicted by black dots. (p-value < 0.05, $n = 41$)
- Upper-right: Positive or negative trend increasement (red and blue box) of each turbulence index for 41 years on DJF over (a) East Asia, (b) Eastern Pacific, and (c) Atlantic.
- Lower-right: MTG mean (pink) and SPD mean (sky blue) and their trends (pink dashed and sky blue dashed lines) for 41 years on DJF over (a) East Asia, (b) Eastern Pacific, and (c) Atlantic regions in NH.

Long-term trend in CAT climatology



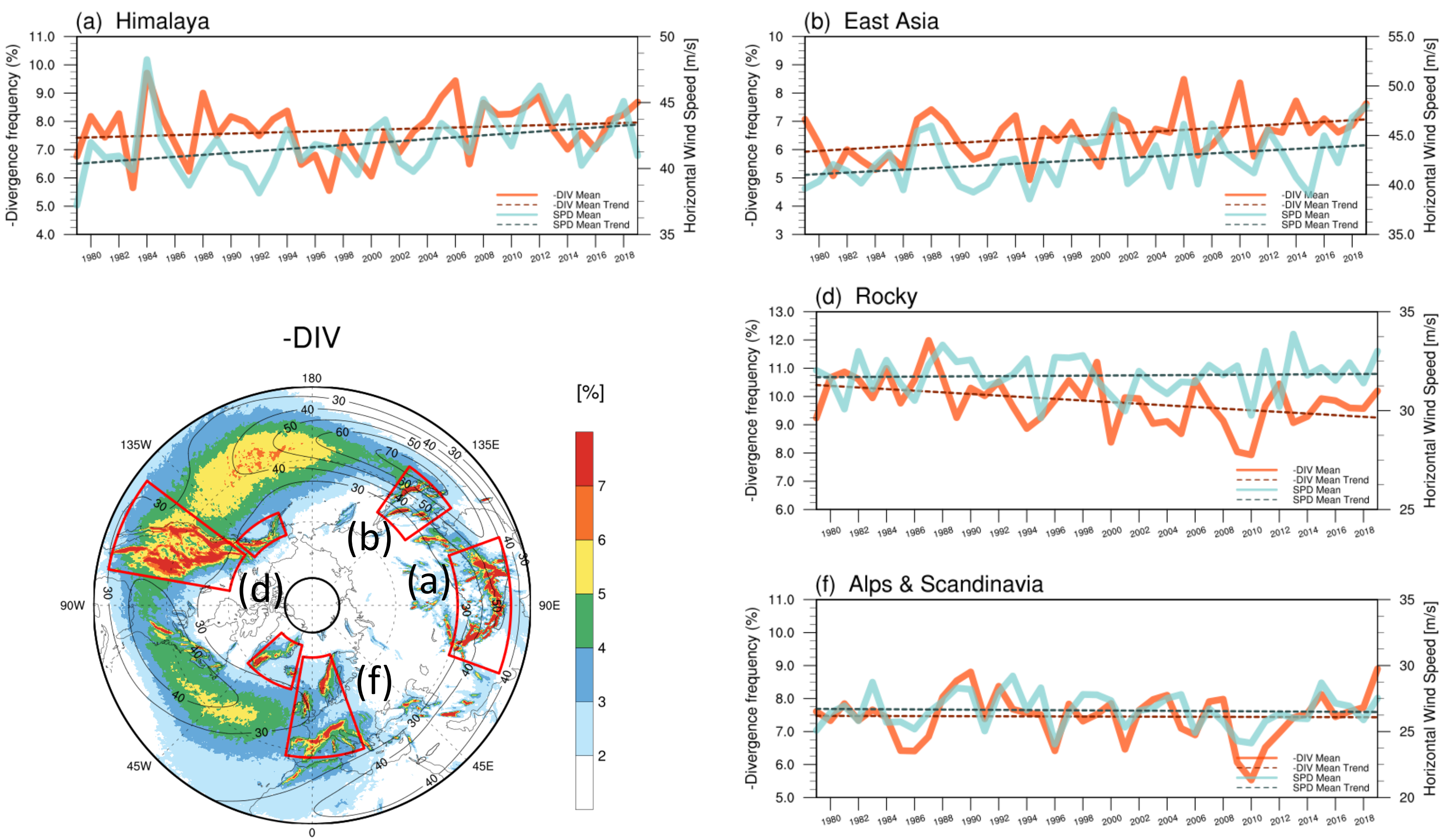


- PDFs of (left) VWS and (right) TI1 calculated at 250hPa over East Asia (80˚-150˚E, 30˚-45˚N) on winter time. Red and blue histogram indicates distribution from 1979 to 1999 and from 2000 to 2019 respectively. Column lines show top 5% value of 1979-1999 PDF (black dashed line) and 2000-2019 PDF (black solid line).

	1979-1999 Threshold (95th percentile)	**2000-2019 Threshold (95th percentile)**	**Increasement (%)**
VWS	0.01264	0.01320	4.43
TI1	1.1017×10^{-6}	1.1746×10^{-6}	6.62

Long-term trend in MWT climatology

- Divergence term (and some others) in ERA5 can capture MWT signals in high-mountain regions.
- Long-term trends in high-mountain regions over (a) Himalaya, (b) East Asia, (c) Alaska, (d) Rocky, (e) Greenland, and (f) Europe are shown with those for upper-level jets.
- -DIV can capture not only MWT but also CAT → Require more rigorous MWT diagnostics.



Summary and Conclusions

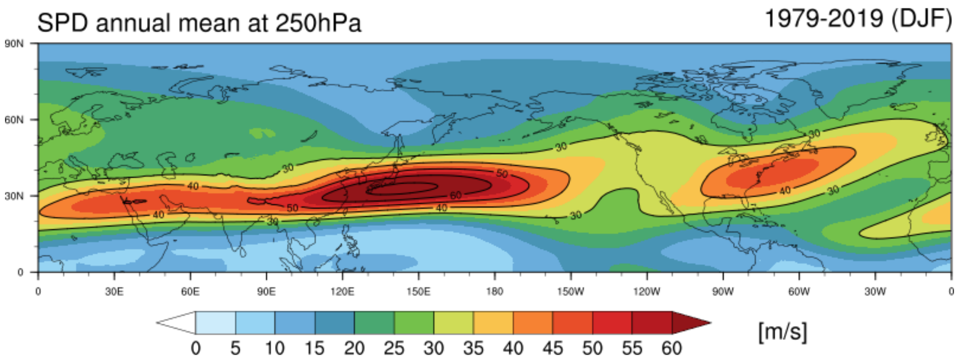
Data and Methodology

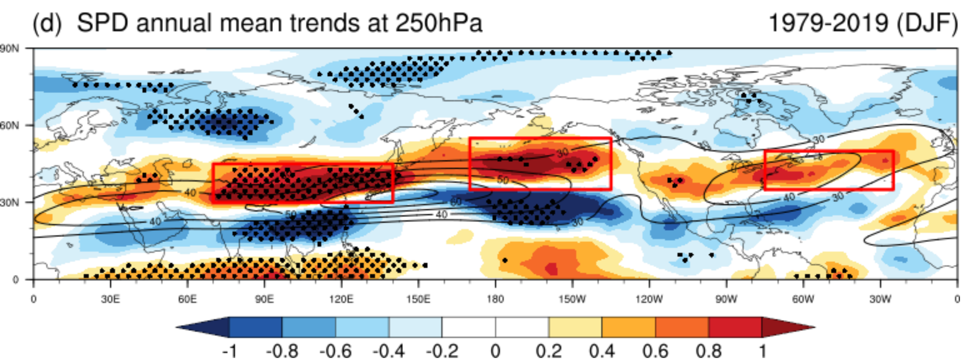
- Multiple sources of CAT are calculated by various CAT diagnostics using ERA5 data.
- Thresholds for MOG-level (hazardous) CAT occurrence are determined by top 5% values of Probability Density Functions (PDFs) for CAT diagnostics.

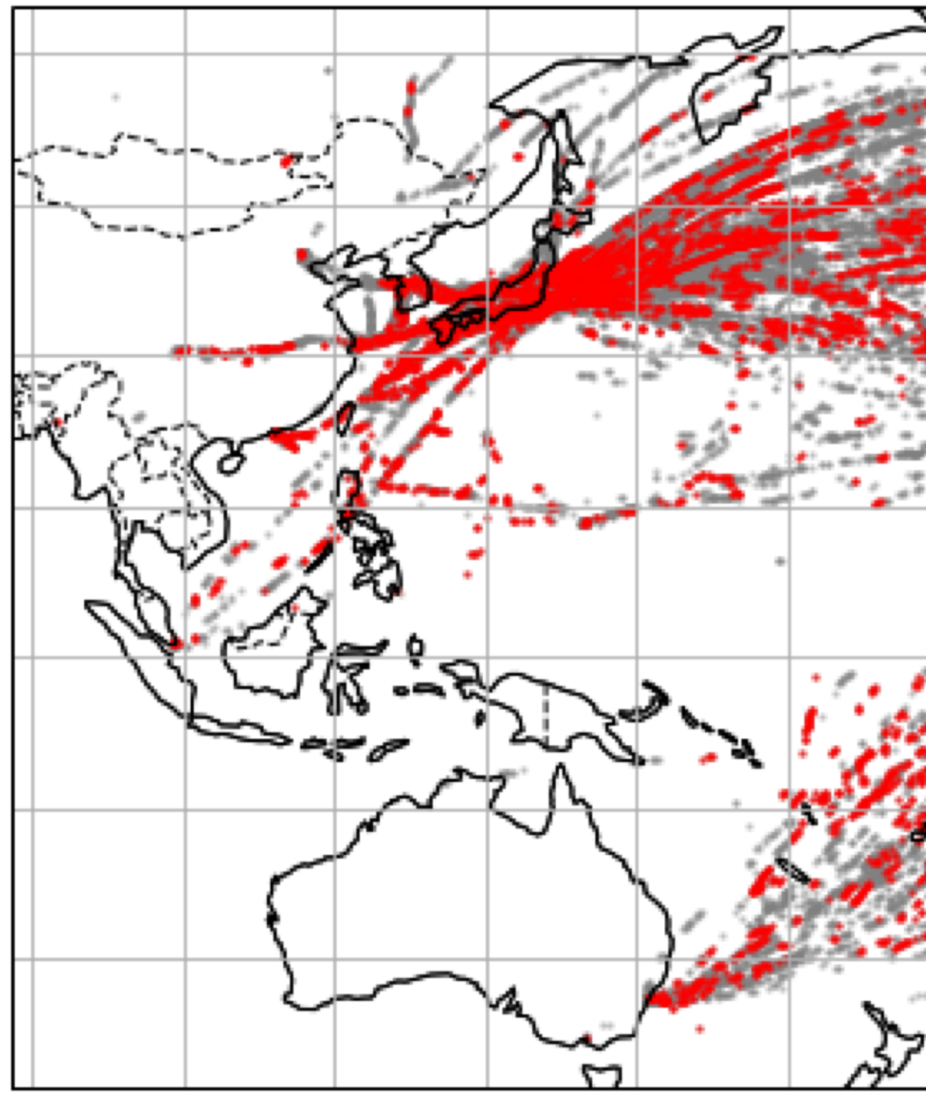
Results

- A case study for CAT event confirms that the calculated thresholds of CAT indices were working well under the strong vertical wind shear with upper-level jet stream.
- Horizontal and vertical distributions of CAT climatology in northern hemisphere (NH):
  - High frequency occurs in the East Asia, Eastern Pacific, and North Atlantic regions associated with the position of upper-level jet streams in NH.
  - Jet entrance and exit regions as well as anti-cyclonic shear side of jet streak have different features of the CAT occurrence with different generation mechanisms.
- Long-term trends in vertical wind shear with upper-level jets are highly correlated with meridional temperature gradients, which results in an increasing trend in CAT indices especially in East Asia, Eastern Pacific, and Northern Atlantic regions.
- **The most significant increase trend of CAT and possible MWT is in the East Asia.**

Summary and Conclusions







[2019.08 – 2021.07 AMDAR EDR data]

- **East Asia has the strongest jet stream in Northern Hemisphere**.
- It has a significant increasing trend in upper level jet in East Asia, which has high traffic between East Asia and US.

Thank you for your attention !

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