Global distribution of tenuous cloud in the tropical tropopause layer

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1. Introduction

[Thin (Subvisible, Tenuous) Cirrus Cloud]

- Its important roles: 1) Radiative balance, 2) Sink for ST Water vapor, 3) Removal of ST aerosol
- Horizontal extent of ~3000 km, and a vertical thickness of 200-300~m
- Mechanisms of formation: 1) Spreading from anvil
  2) Cooling due to large-scale upwelling

[Graph and data]

Backscattering Ratio at 1064 nm (z=17 km 10° S)

Haynes et al. [2001]
Cirrus occurrence related to downward propagating wave
[Boehm & Verlinde, 2000]
Waves control water vapor entering the ST
[Fujiwara et al., 2001]
Questions:
- What effect on radiation/dehydration? ~ $n(r)$, $\int n(r)r^2dr$, $\int n(r)r^3dr$
- What effect on ozone chemistry? ~ Chemical compounds

Short term variations of cirrus cloud in the TTL in terms of vertical and global distribution
2. Data and Analysis

[HALOE trace gas data]

- Spices: Aerosol extinction (5.26 μm), O₃, H₂O
- Solar occultation techniques
- Period: 1991-1999
- Grid interval: 24° × ~5° × ~500m
- Tropical observation for 7-10 days 10 times every year
  ⇒ Short term time evolution

HALOE longitude (10N-10S)
[Identification of tenuous cloud]

- $Z_{CT}$: The altitude where the extinction coeff. $\kappa$ at 5.26 $\text{m}$ becomes less than 0.05.

- $Z_{\sigma}$: The altitude where the spectral variance $\sigma$ of four WL (2.45-5.26 $\text{m}$) < 0.05

[Climate elements]

- UKMO stratospheric analysis: $T$ (15S-15N mean)
- Singapore rawinsonde data: $T, u, Ri$
  - $Z_{CP}$: Cold Point Tropopause
- NOAA: Outgoing Longwave Radiation (OLR) (min in 15S-15N)
3. Results

A. A case study for January 1993
TC with T at 100hPa and OLR (15S-15N)

Eastward propagation

Cold Anomaly

Jan-Feb, 1993
Color: 100hPa
--- :7 m/s (65 day)
------- :30 m/s (13 day)

- TC: A good agreement with the regions of active convection & 100-hPa cold anomaly
- Global-scale occurrence
- Cold anomalies coupled with the MJO convection exist to the east of the MJO convection
[ Time evolution of lon-z section ]

- Animation (17-31 January, 1993)

Color: 100 hPa

- : $Z_{CT}$
- : $Z_{CCT}$
- : $T$ at 195, 197 K
Difference between $Z_{CT}$ & $Z_{CCT}$ (3~km)
Thick cloud on the eastern side of the convection

OLR anomaly: at western edge of cold anomaly

Color:
- $Z_{CT}$
- $Z_{CCT}$
TC: well confined to cold anomaly above the convection
TP: the MJO-related anomaly (~7 m/s)
ST: anomaly of the Kelvin wave (20-30 m/s)
Time evolution over Singapore

- TC: confined to the regions of cold and easterly shear
- Cooling phase: upwelling & cooling
- Warming phase: easterly & downwelling
- “Kelvin wave”
- After warming: the appearance of small
  - evaporation and sedimentation
- TC: approaches ST aerosol layer
  - possible K-H instability
■ TC: in the anomalies of cold & easterly shear, and below the regions of warm & westerly shear
■ □ : “layer structure” ~ geometric thickness of 2~km spreading from high convection (~Z_{CP})
[Scattering plot of TC]

- TC: below 370 K (~100 hPa)
- Variations on the isentropic surfaces
  - Quasi-isentropic transport, but sedimentation and evaporation
- TC: $T_{anm} < \sim 0$ K & $u < 0$ m/s
- $\max$: $T_{anm} \sim 0$ & $u \sim 0$
- near convective cloud top $Z_{CCT}$
3. Results

B. Statistical Analysis for 1995-2000
Large variance of $\mathcal{D}$ & $\mathcal{F}$ relative to dynamical fields

- Seasonal cycles and sedimentation/evaporation
- Layered structure of $\mathcal{D}$ ~a geometric thickness of 2 km
- At the edge of and between convection clouds
TC occurrence below $\sim 400$ K ($\sim 80$ hPa) over Singapore

TC starts to appear at $T_{\text{anm}} < +1$ K & $u < 0$ m/s

$\theta_{\text{max}}$: at the bottom of the anomalies of cold and easterly

Convective clouds are expected to have large $\theta$ in the $T_{\text{anm}} > 0$ K, $u_{\text{anm}} > 0$ m/s
[A comparison between $Z_{CT}$, $Z_{\perp}$, and $Z_{CCT}$]

- TC: ~2-3 km higher than $Z_{CCT}$
- The median of $Z_{TC}$: at 16 km, independent of $Z_{CCT}$
- TC: mainly within ~2 km of $Z_{CP}$
- Bimodal PDF in the $Z_{CP}$-$Z_{CCT}$ plot: related to the jump-up of $Z_{CP}$
[Composite Analysis - Singapore $T$, $u$ & HALOE $\beta$]

- Cirrus occurrence coupled with Kelvin wave and MJO

Key days: $T_{100}$ min during the cold phase of MJO

- Singapore original $T$
- MJO component (30-90 days) of $T$
[Composite analysis – Singapore T, u & HALOE Z<sub>CT</sub>]

Shading: T<sub>anm</sub>, :193, 195K, □ : Z<sub>CT</sub>, □ : Z<sub>CP</sub>

- | Z<sub>CT</sub>' | >> | Z<sub>CP</sub>' |
- The highest Z<sub>CT</sub>: above the TP warming related with the MJO
- The other high Z<sub>CT</sub>: related with cold anomaly of the Kelvin wave (coupled with SCC ?)

- Cirrus occurrence is also enhanced by WAVES
[ and ozone anomaly in December, 2001]
[Mechanisms of occurrence of cirrus clouds]

1) Spreading of anvil from convection
2) Large-scale upwelling of wave
3) Wave-convection coupled system with 1) and 2)
[Microphysical Consideration]

- **Massie et al. [2002]: HALOE extinction data**
  - Transformation from $\mathcal{K}$ (km$^{-1}$) to $V$ (m$^3$ cm$^{-3}$)
  - The calculation based on the Mie theory
  - Using ASHOE-MAESA cirrus size distribution
    $$ V = \exp(a + bB + ...) ; \ a = 11.14, \ b = 1.380, \ B = a \log(\mathcal{K}) $$

- **Convective cloud**: $\mathcal{K} > 10^{-2}$ km$^{-1}$, $V > 200$ m$^3$ cm$^{-3}$
  - Heats the air through condensation in the upwelling

- **Tenuous cloud**: $\mathcal{K} \sim 10^{-2.5}$ km$^{-1}$, $V \sim 50$ m$^3$ cm$^{-3}$
  - Baumgardner et al. [1995, 96]: $r \sim 0.7-2.8$ m below $T_{ice}$
  - Cloud particles cannot fall out in a few days
  - For $\mathcal{K} \sim 0$, $r > 10$ m from the Mie theory
    - Cloud particles can depart from the surface, but cannot heat the atmosphere
[Mechanisms of occurrence of cirrus clouds]

1) Spreading of anvil from convection
2) Large-scale upwelling of wave
3) Wave-convection coupled system with 1) and 2)

adiabatic warming
adiabatic cooling

\( r_{\text{eff}} \sim O(1-10) \ \text{m} \)
\( V \sim 50 \ \text{m}^3 \text{ cm}^{-3} \)

\( r_{\text{eff}} \sim O(100-\text{~}) \ \text{m} \)
\( V > O(10^2) \ \text{m}^3 \text{ cm}^{-3} \)

30 m/s
7 m/s
70 hPa
100 hPa
150-200 hPa
1000 hPa

longitude

7 hPa
10 hPa
150-200 hPa
1000 hPa

evaporation & sedimentation
nucleation \( T_{\text{anm}} < +1 \text{K} \)
condensational heating
4. Conclusions

- HALOE extinction data shows the occurrence of TC on a global scale with a WN of 1-3 and an east-upward tilt in January, 1993.
- Variations of TC are coupled with cold anomalies of the equatorial Kelvin wave in conjunction with:
  1) the active convection of the MJO with a phase speed of about 7 m/s (60-200E)
  2) the SCC with a phase speed of 20-30 m/s

* An upward-westward tilt of TC and temperature anomaly can be observed in low latitudes and even in the tropics when the Kelvin wave activity is weak.

- The occurrence of TC could be enhanced by various waves closely connected with convective system.
4. Conclusions (continued)

- **On the eastward side (prior to the occurrence) of MJO/SCC:**
  - TC occurs through water supply from convective outflow / condensation within cold anomaly caused by adiabatic/radiative cooling above the convective warming anomaly
  - A geometric thickness of ~4 km
  - Mechanism: large scale-upwelling / convective out-flow

- **On the western side (after the occurrence) of MJO/SCC:**
  - TC is transported downward-westward by downwelling and easterly, and disappear due to sedimentation/evaporation as the air adiabatically warms.
  - A geometric thickness of ~2 km
  - Mechanism: convective out-flow