Observations of Ozone, Water Vapor, and Cirrus in the Tropical Tropopause Layer over the Pacific

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SPARC 2008 General Assembly

Part I. Ozone obs. in the TTL
- **(1) Equatorial Kelvin waves**
- **(2) Transport from midlatitude LS**

Part II. WV obs. in the TTL → "WV MATCH" by Hasebe et al.

Part III. Cirrus obs. in the TTL
- **Three northern-winter campaigns in the tropical western Pacific**
- **Several dynamical processes controlling TTL cirrus**

Part I. Ozone obs. in the TTL

Ozonesonde measurements (e.g., by the Southern Hemisphere Additional Ozonesondes, SHADOZ) have revealed:

(1) Dynamical structure of the "Tropical Tropopause Layer" (TTL)
. . . as a steady state
(e.g., Folkins et al., JGR, 1999 →)

(2) Transport processes in the TTL
. . . from variability of ozone
→ Two campaigns in Indonesia have revealed

(2-1) Role of equatorial Kelvin waves

(2-2) Transport from midlatitude lower stratosphere

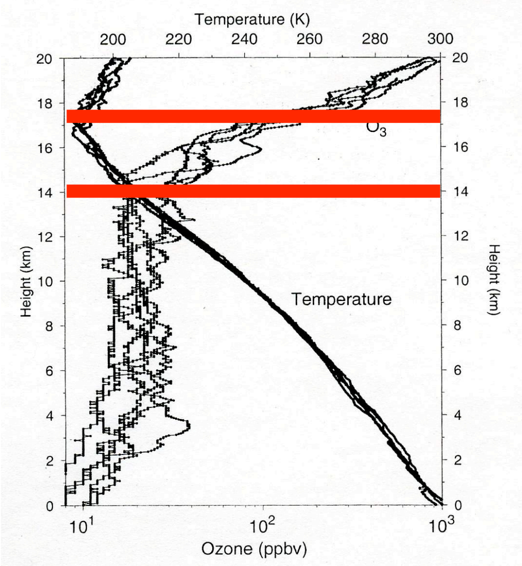
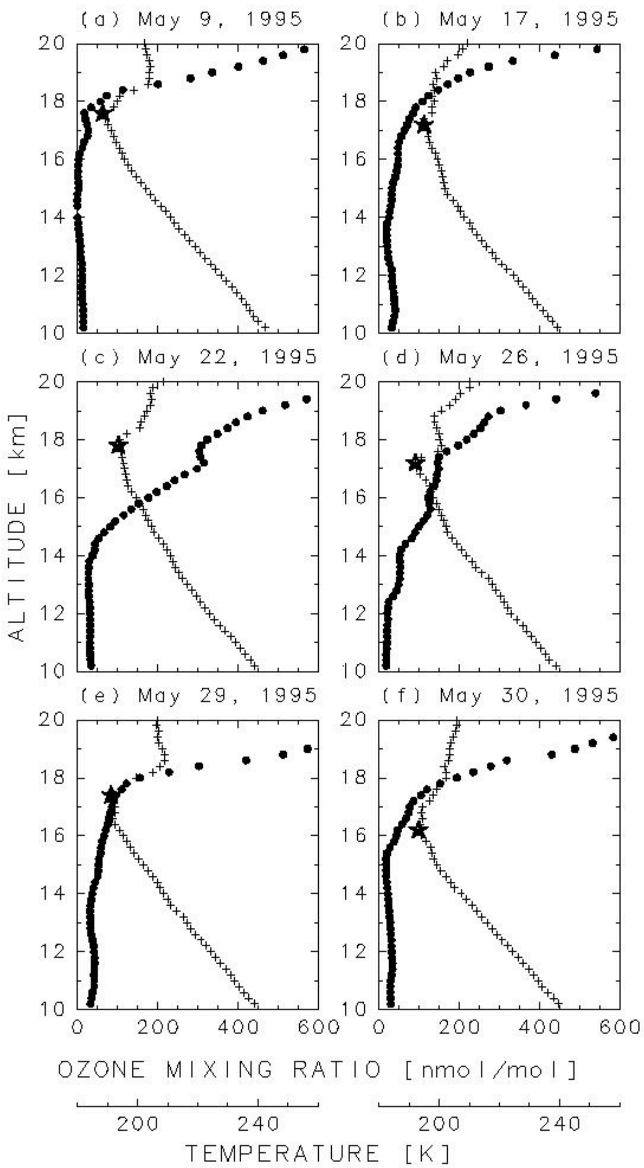
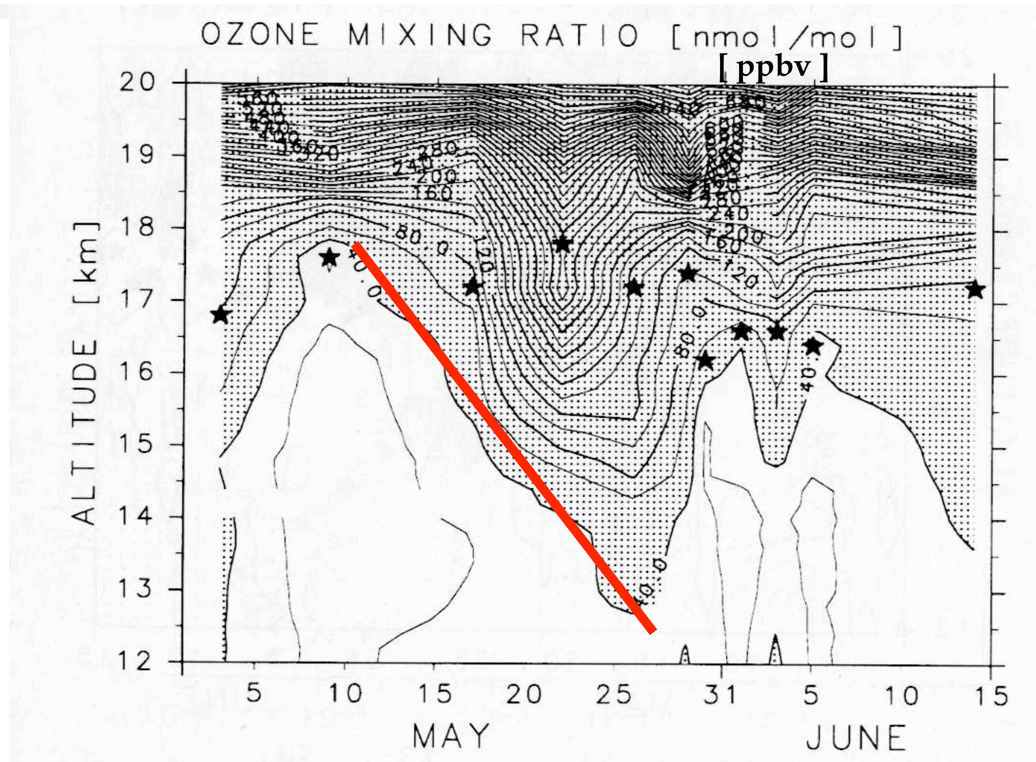


Figure 1. Profiles of temperature and O_3 taken from five ozonesondes launched Samoa in March 1996.

(Samoa, March 1996)

Ozonesondes in Indonesia

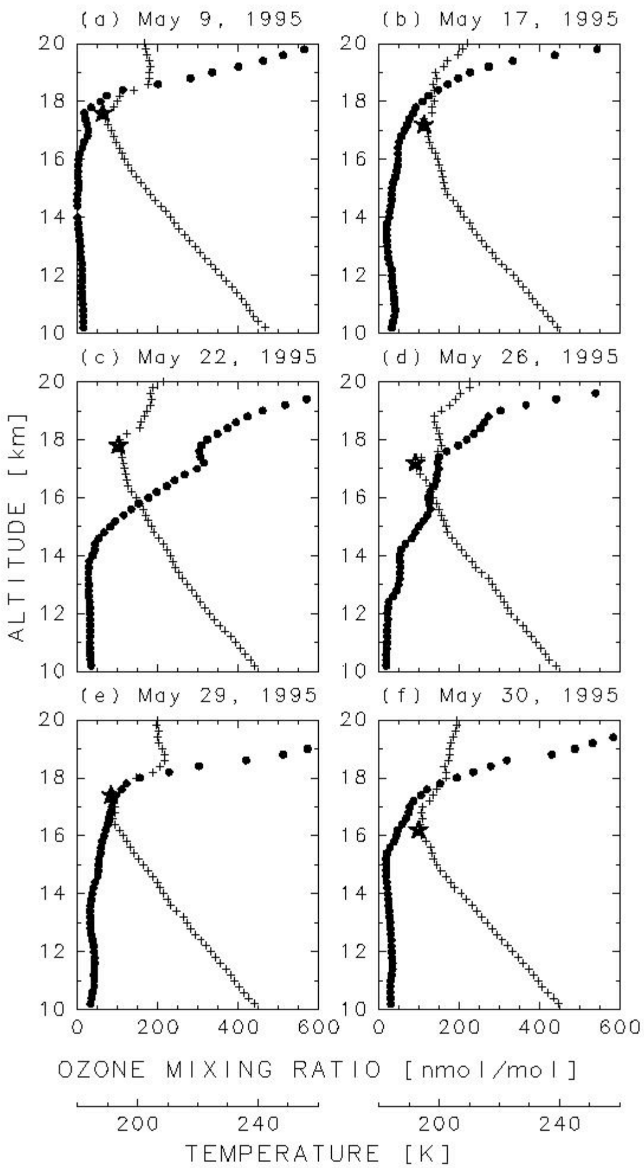


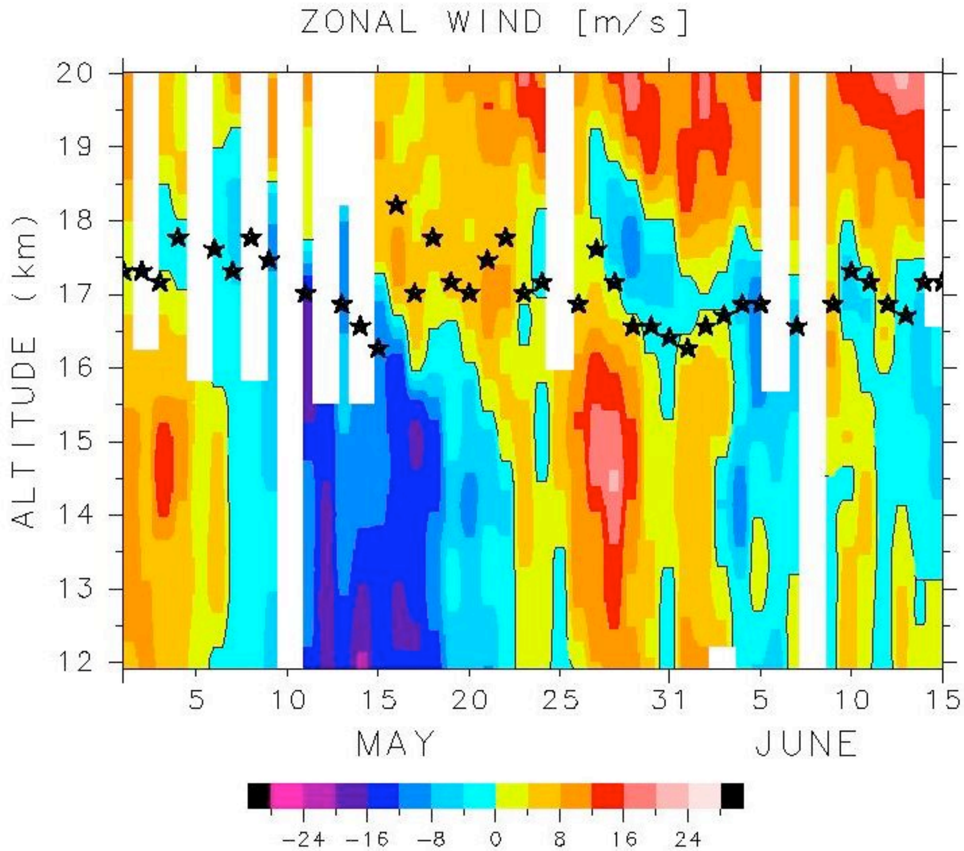


Ozonesondes at Watukosek, Indonesia (1995)

[Fujiwara, Kita, and Ogawa, JGR, 1998]

Ozonesondes in Indonesia

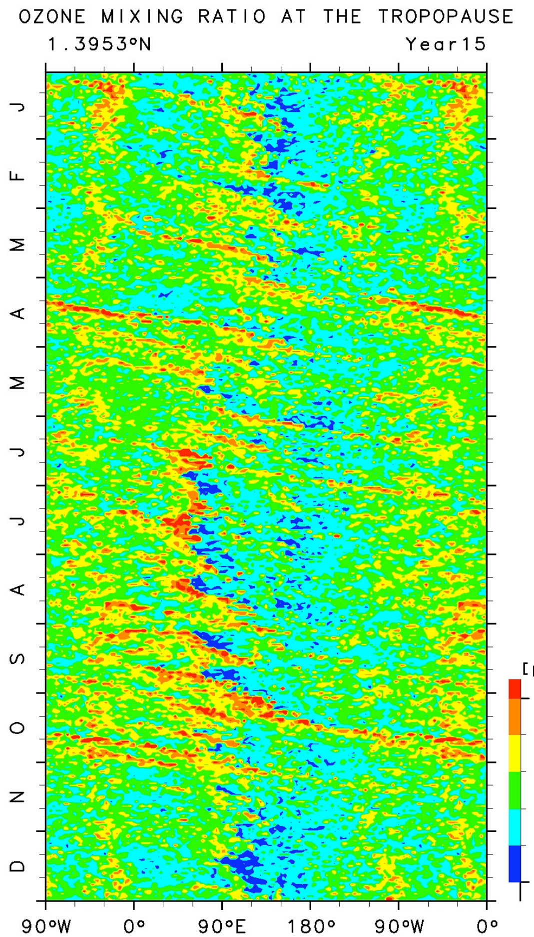


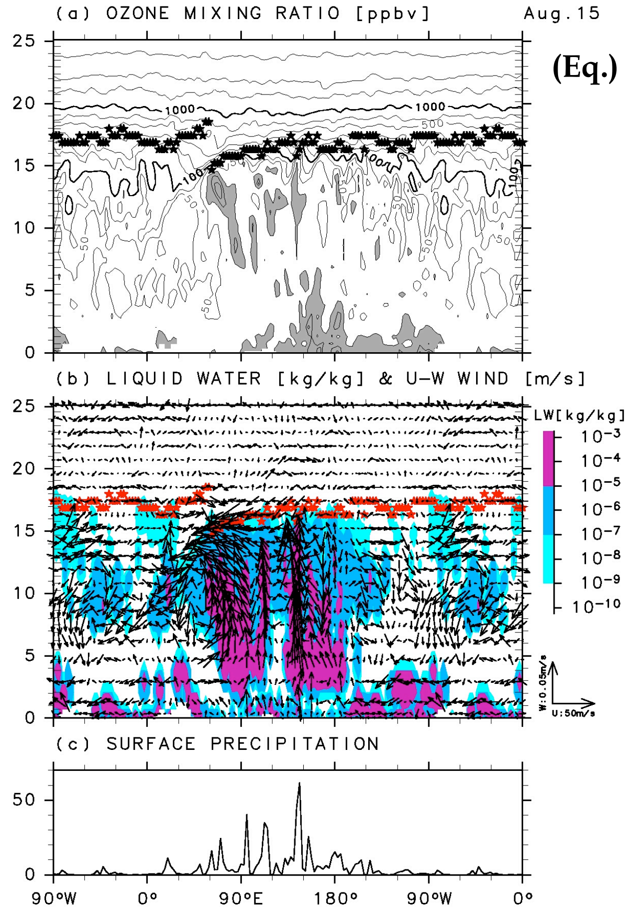


- 20-day osicllation
  TTL: Large-amplitude (breaking) Kelvin waves
  Tropo: Organized convection (ISO)
- Ozone transport at downward displacement phase
- Wave breaking → mixing & irreversible transport

[Fujiwara, Kita, and Ogawa, JGR, 1998]

Kelvin waves in the TTL





- Eastward-moving large-scale disturbances are dominant at the equatorial tropopause
- Most of them are breaking Kelvin waves

- In the eastern hemisphere, these waves are often associated with organized convections (ISO, etc.)

- At downward displ. phases, ozone-rich, dry air transport into TTL
- At upward displ. phases, cold anomalies prevent TTL from excess water

→ **"Dehydration Pump"**
[Fujiwara et al., GRL, 2001]

CCSR/NIES AGCM T42<u>L60</u> (dz∼550 m in UT/LS)
+ simplified stratospheric ozone chemistry
[Fujiwara and Takahashi, JGR, 2001]

(Climatology of TTL Kelvin waves in ERA40 by Suzuki and Shiotani, JGR, 2008)

Ozonesondes in Indonesia [2]

Soundings at two equatorial western Indonesian stations (Kototabang & Pontianak)

(Distance ~ 100 km)

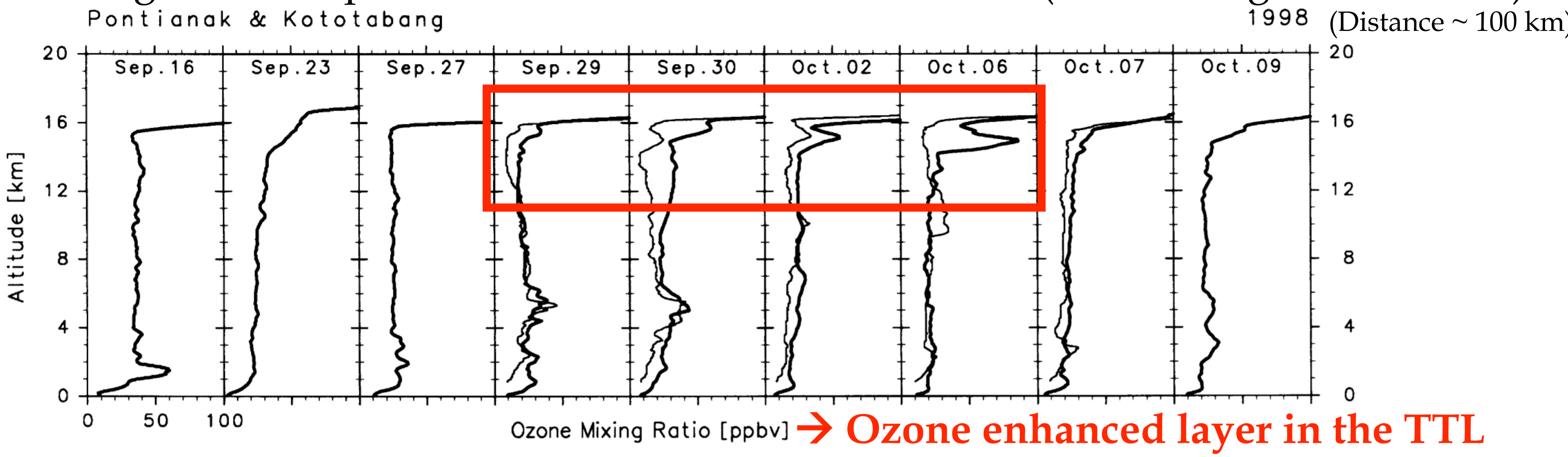


Fig. 4. Tropospheric ozone profiles at Pontianak (thick curves) and at Kototabang (thin curves) in September–October 1998.

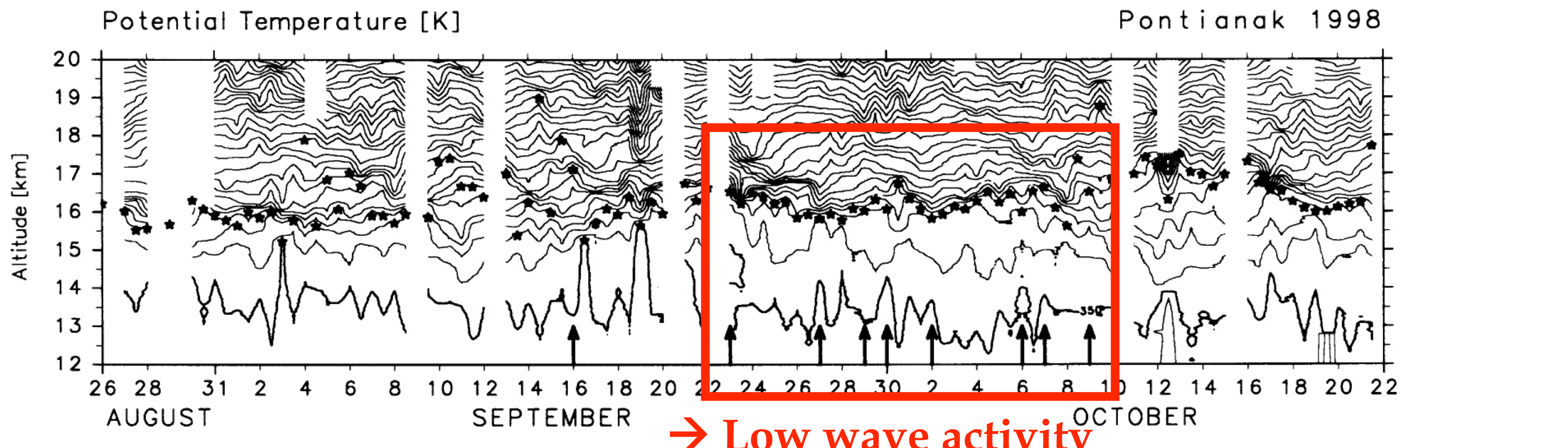


Fig. 5. Time–altitude distributions of potential temperature at Pontianak between 26 August and 21 October, 1998 in the 12–20-km region. The contour interval is 5 K. The thick curves are for 350 K. The location of the tropopause defined by the temperature minimum is indicated by stars. The arrows indicate the ozonesonde soundings at this station.

[Fujiwara, Tomikawa, et al., Atmos. Env., 2003]

(a) Transport from the equatorial LS? → No, because of low wave activity
(b) Transport of air affected by biomass burning and pollution? → No.
(c) Trajectory analysis and Reverse Domain Filling (RDF) PV analysis
→ Enhanced ozone originated from the northern midlatitude LS

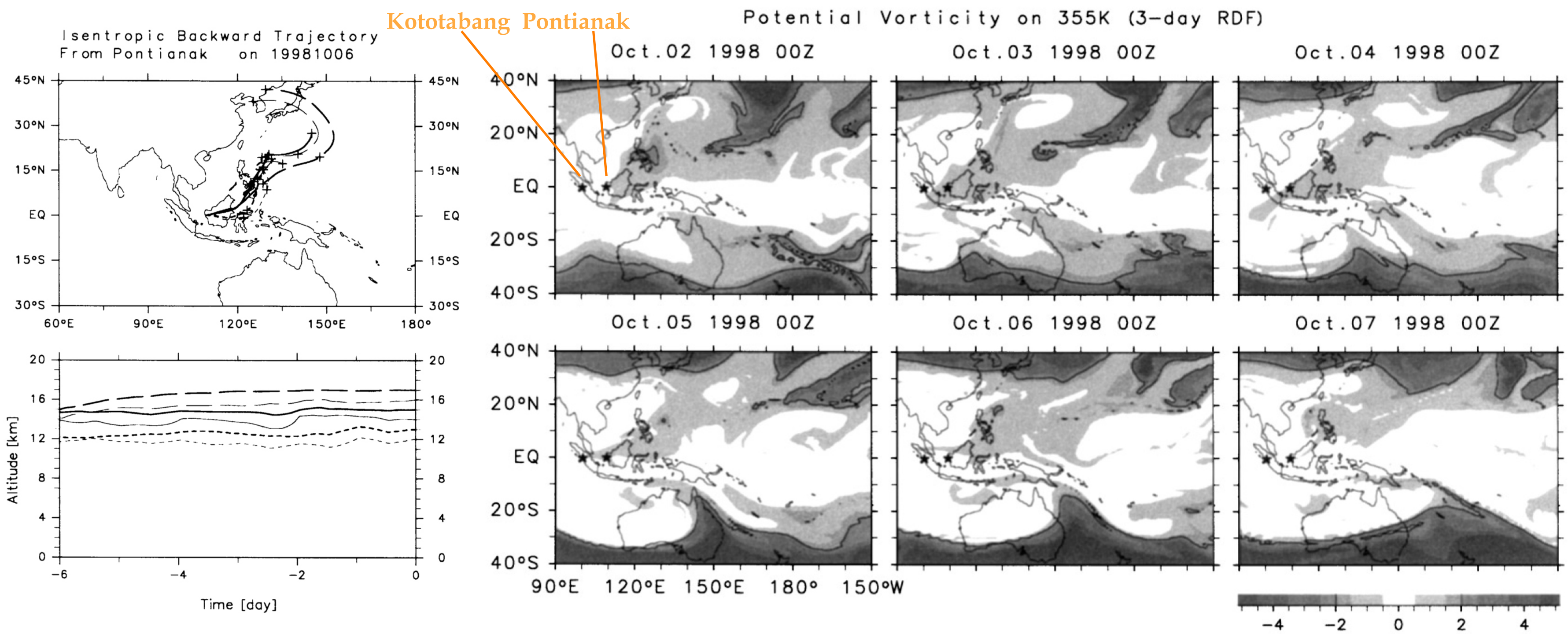


Fig. 7. PV distributions on the 355-K isentropic surface on 2–7 October 1998 by the 3-day RDF calculations (see text for the details). The unit is pvu, where 1 pvu = 10^{-6} m^2 s^{-1} K kg^{-1}. The contour lines for ±2 pvu are also indicated. Pontianak and Kototabang are indicated by stars.

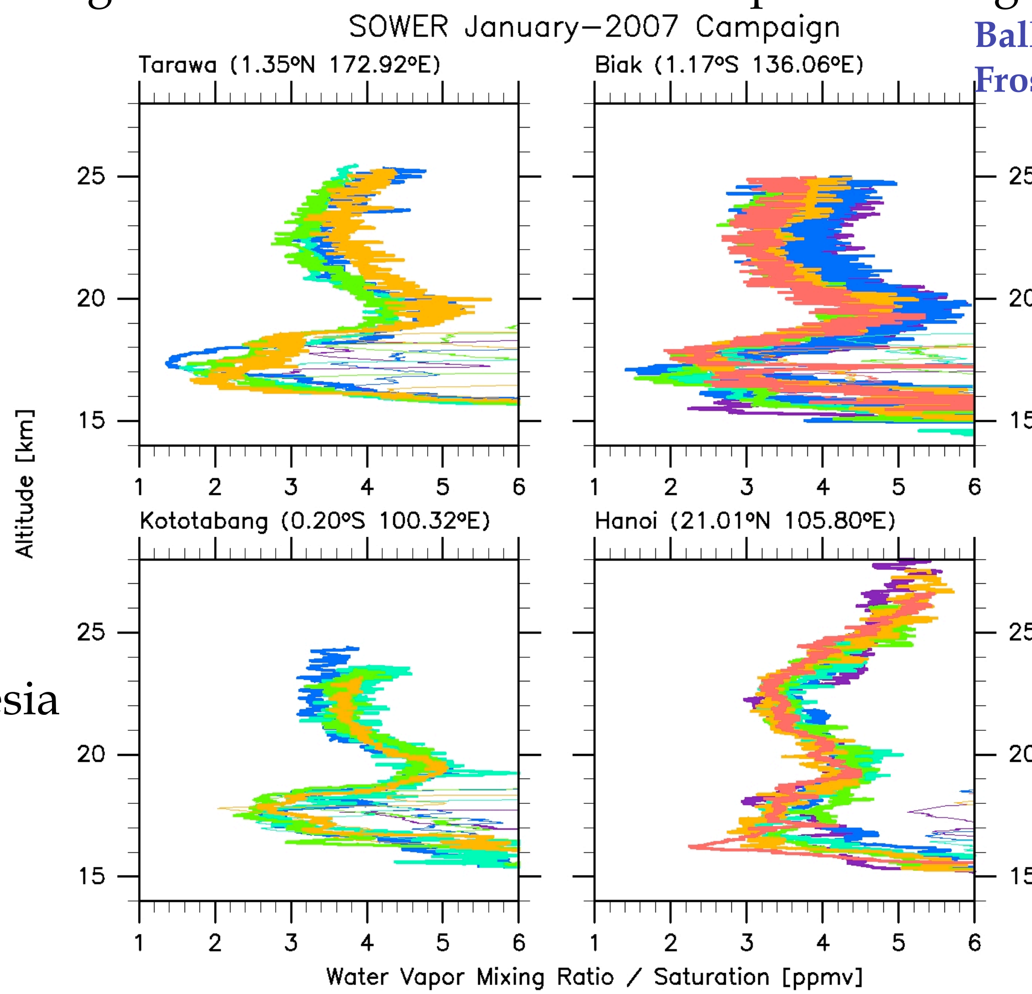
[Fujiwara, Tomikawa, et al., Atmos. Env., 2003]

Subtropical STE associated with Rossby wave breaking events
(e.g., Postel and Hitchman, JAS, 1999; Waugh and Polvani, GRL, 2000)
cause ozone-rich, dry air (horizontal) transport into the TTL .
Ozonesonde measurements provide the evidence.

Part II. WV obs. in the TTL

January 2007 campaign of
the Soundings of Ozone and Water in the Equatorial Region (SOWER)

Balloon-borne Cryogenic Frostpoint Hygrometer (CFH)



Tarawa, Western Pacific

Biak, Eastern Indonesia

Kototabang, Western Indonesia

Hanoi, Southeast Asia

<with Hasebe, Shiotani, Voemel, Ogino, Iwasaki, Shibata, and local collaborators>

Part III. Cirrus obs. in the TTL

- Co-workers:

  S. Iwasaki (NDA), A. Shimizu (NIES), Y. Inai (Hokkaido U.),
  M. Shiotani, (Kyoto U.), F. Hasebe (H. U.),
  I. Matsui, N. Sugimoto (NIES), H. Okamoto (Tohoku U.) ,
  N. Nishi, A. Hamada (K. U.), T. Sakazaki (H. U.),
  K. Yoneyama (JAMSTEC)

- Ship-borne lidar and radiosonde measurements in the tropical western Pacific over three northern winters (~1 month each time)
- Controlling processes for the observed TTL cirrus variations mainly from the view point of large-scale meteorology ("weather" in the TTL)

- (Submitted to JGR)

NIES Lidar on R/V Mirai

2-wavelength dual polarization lidar

(National Institute for Environmental Studies, NIES)

Nd:YAG laser (1064 nm & 532 nm)

Range resolution :

6.00 m for MR01 and MR02

3.75 m for MR04

Temporal resolution : 10 sec

Operation :

continuous during day and night for about a month

R/V Mirai :

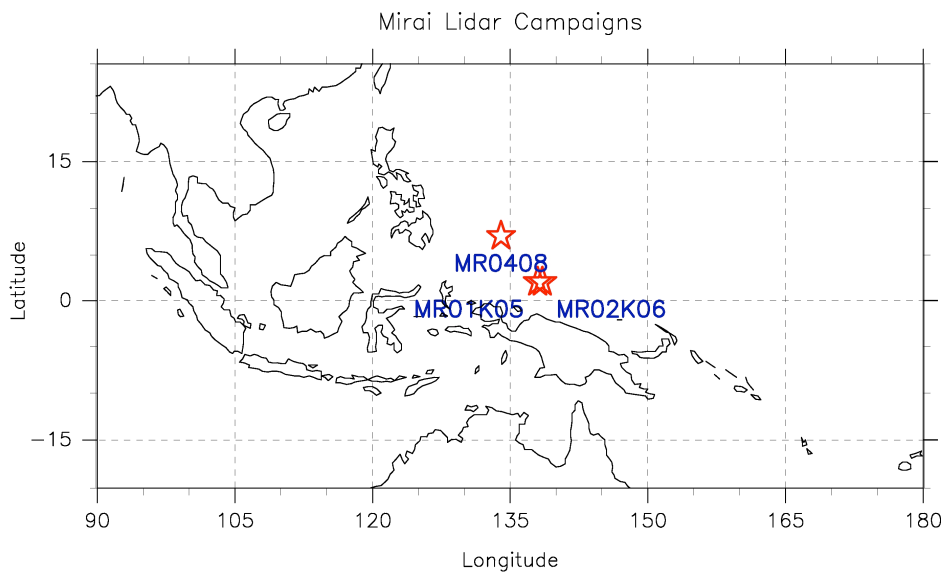
(Japan Agency for Marine-Earth Science and Technology, JAMSTEC)
Atmospheric and Oceanic Research Vessel

Doppler Radar
Radiosonde auto-launcher

Radiosondes at 3-hour intervals for all 3 campaigns

Campaigns in the Western Pacific with NIES Lidar

Cruise Number	Period	Location	3-hourly Radiosondes	Comments
MR01-K05 ("MR01")	**9 Nov. to 9 Dec., 2001**	**2.0 N, 138.0 E**	**RS80-H**	**Sub-Visual Cirrus (SVC)** **(Iwasaki et al., GRL, 2004)**
MR02-K06 ("MR02")	**15 Nov. to 14 Dec., 2002**	**2.0 N, 138.5 E**	**RS80-H**	**Large-amplitude Kelvin-wave event**
MR04-08 ("MR04")	**14 Dec. 2004 to 11 Jan. 2005**	**7.5 N, 134.0 E**	**RS92**	**"Visual" TTL cirrus & Clear diurnal variation**



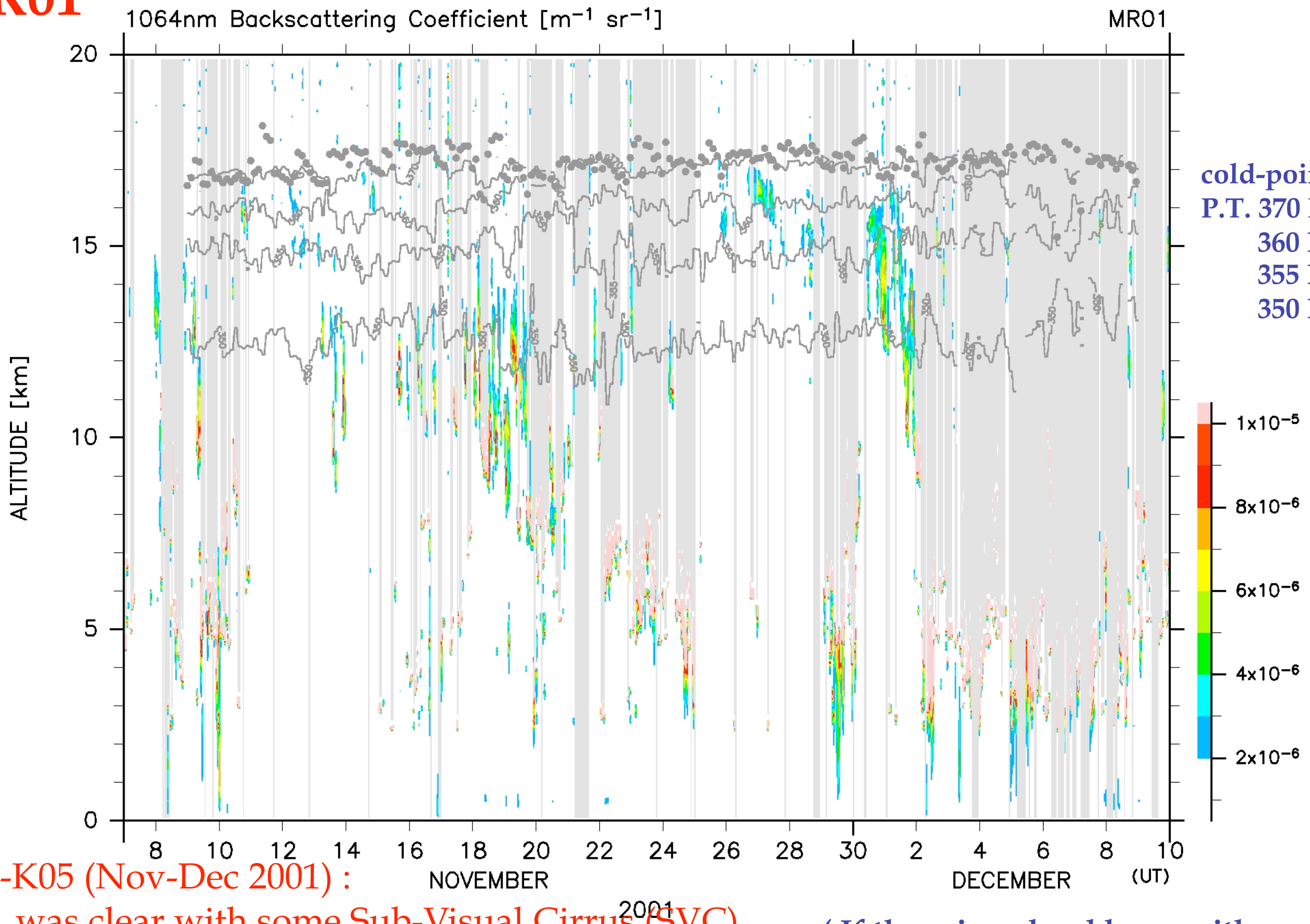
- Lidar equation :

$$P(R) = c\beta(R)\exp\left[-2\int_0^R \alpha(r)\,dr\right] / R^2$$

alpha : extinction coefficient
beta : backscattering coefficient
→ beta(particle) for 1064 nm is used for cloud detection

- Lidar sensitivity (systematic noise level) increased (decreased) from MR01 to MR04

MR01

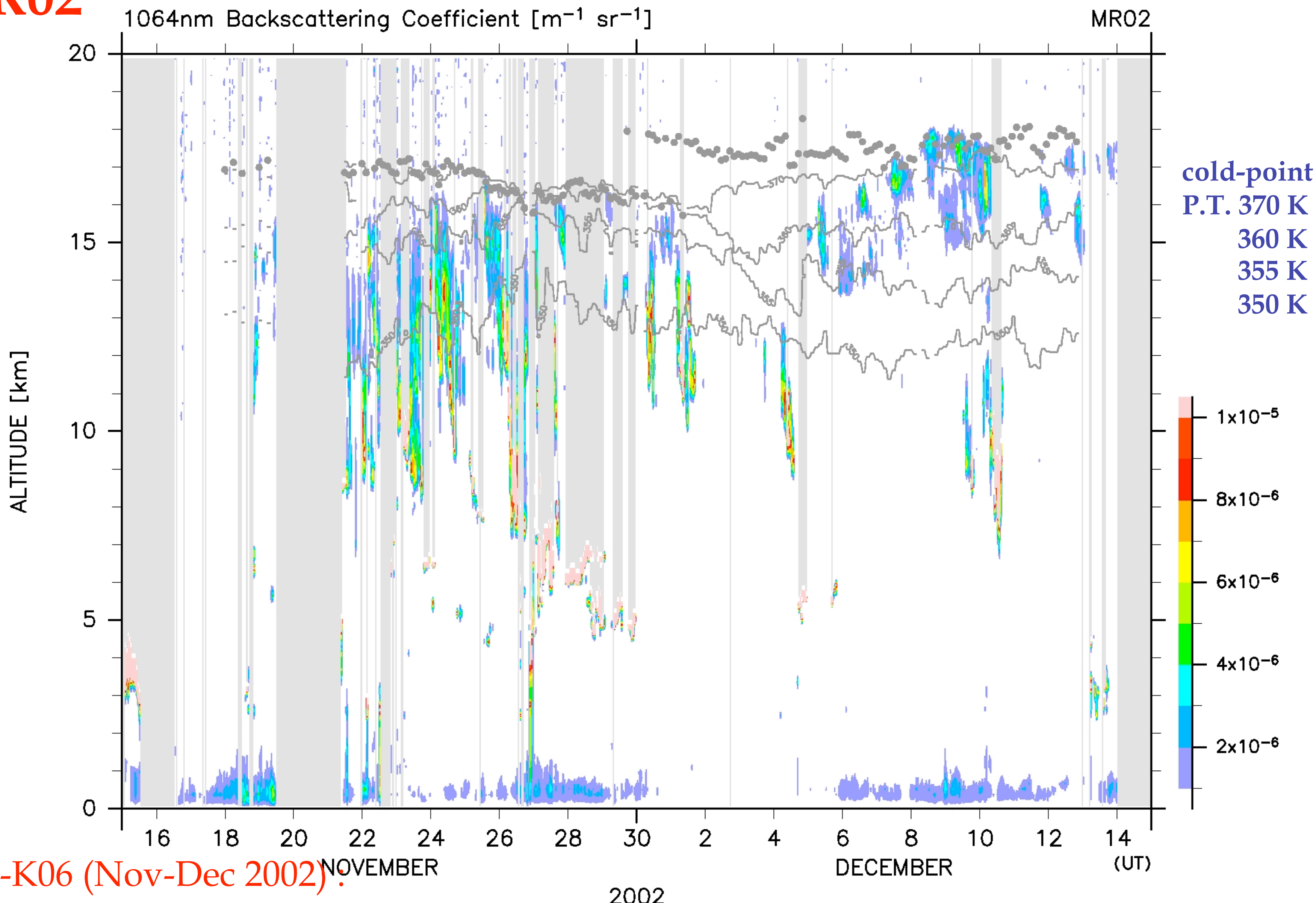


cold-point
P.T. 370 K
360 K
355 K
350 K

MR01-K05 (Nov-Dec 2001) :
TTL was clear with some Sub-Visual Cirrus (SVC).
Optical depths < 0.01 (except for 26-27 & 30-1 cases)
(These SVC were investigated by Iwasaki et al., GRL, 2004)

(If there is a cloud layer with >1.2x10^{-5} m^{-1} sr^{-1}, measurements above are considered missing.)

MR02

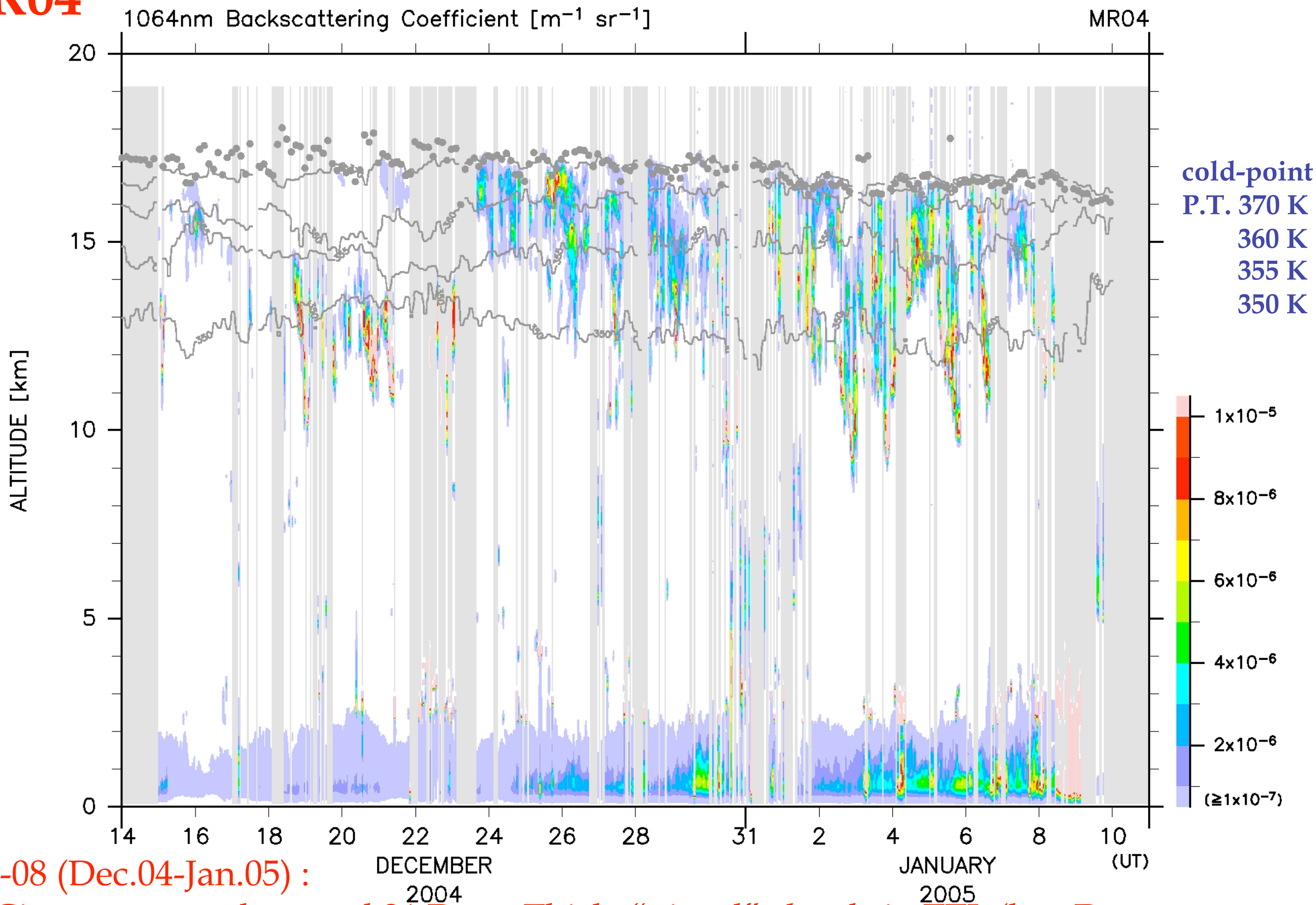


MR02-K06 (Nov-Dec 2002) :

TTL was strongly perturbed (CPT jumped) with a period of ~20 days. → Kelvin wave

Cirrus in the TTL showed corresponding variations to the dynamical variation.

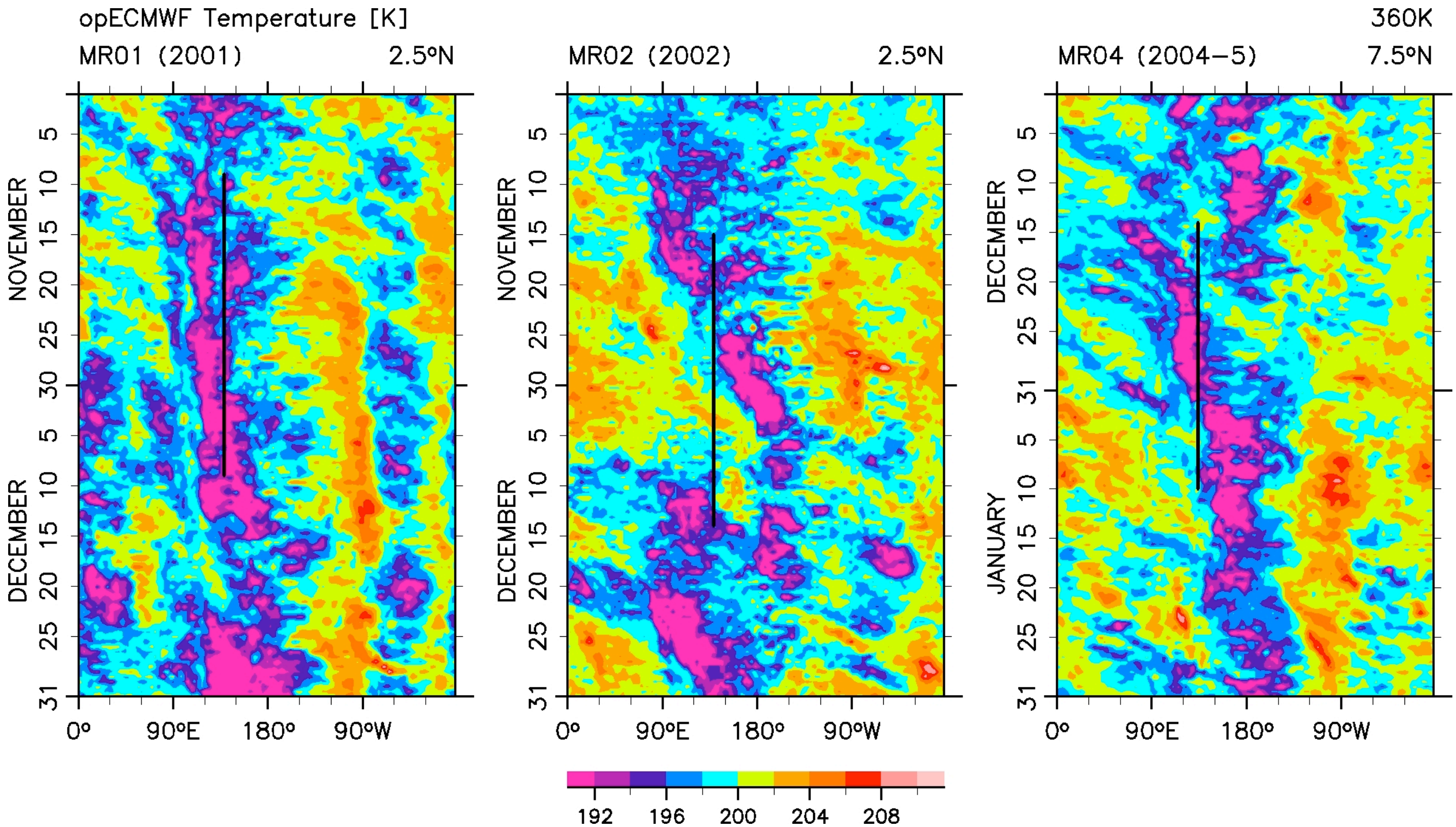
MR04

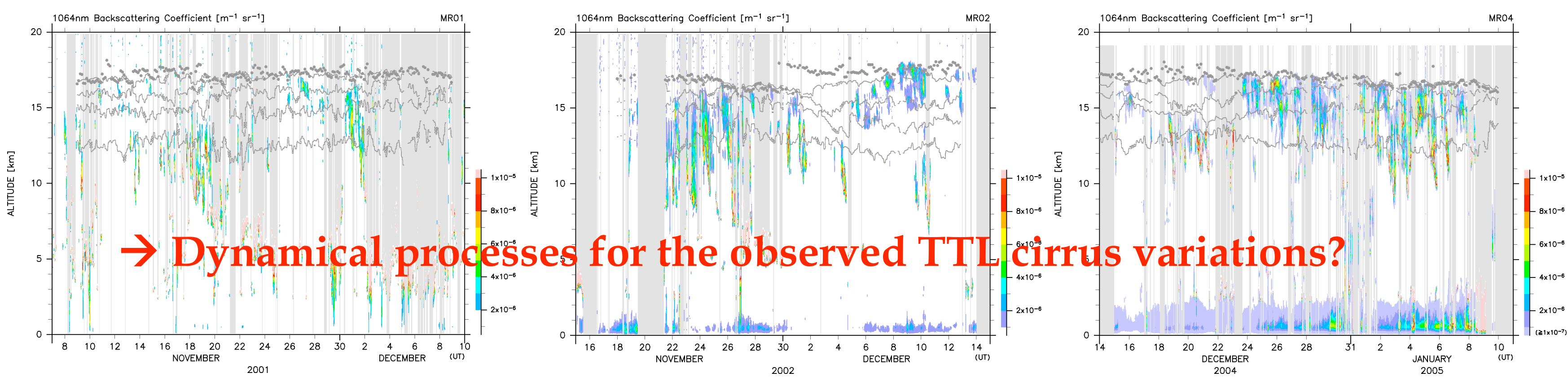


MR04-08 (Dec.04-Jan.05) :

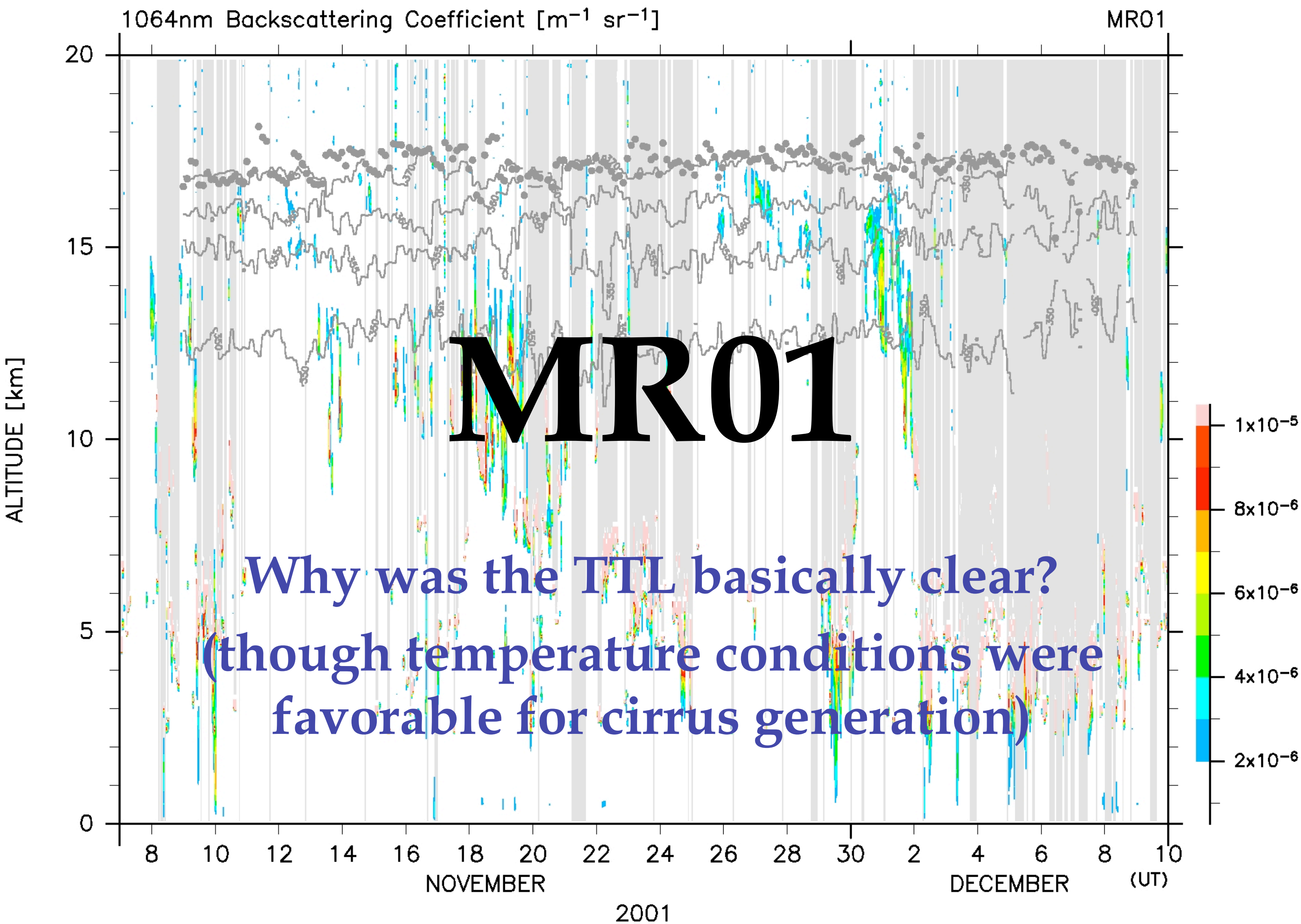
(1) Cirrus appeared around 21 Dec. Thick, "visual" clouds in TTL (late Dec. to early Jan.). Optical depths are 0.1~0.3.

(2) Quasi-steady diurnal variation in early Jan, sedimentation during the nighttime .





→ Dynamical processes for the observed TTL cirrus variations?

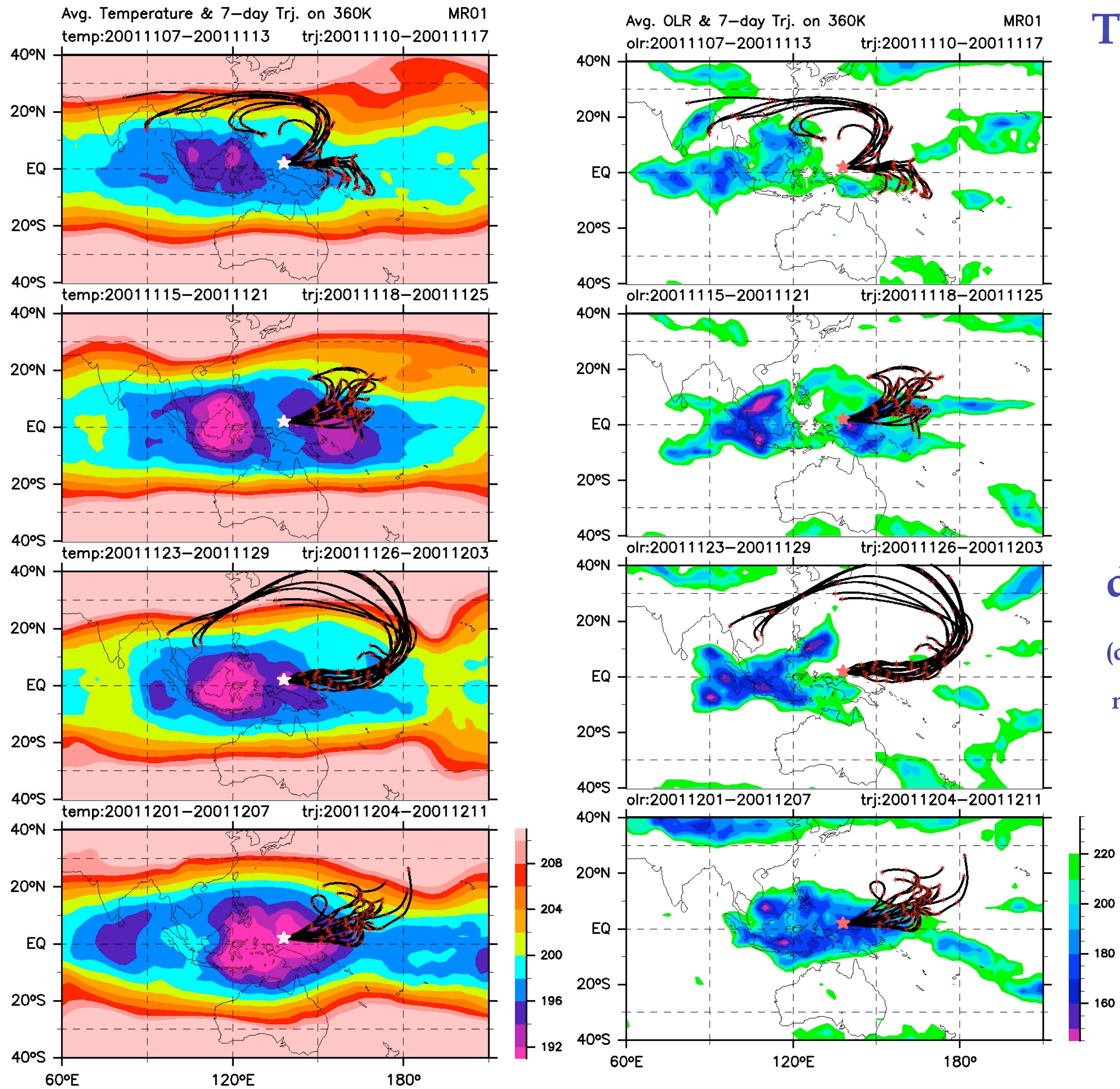


MR01

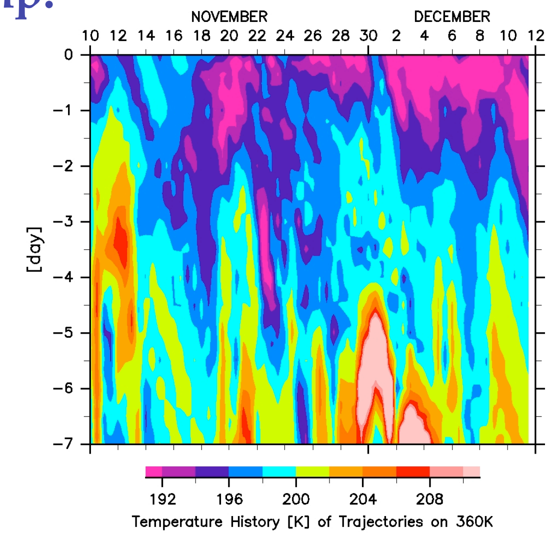
Why was the TTL basically clear?
(though temperature conditions were favorable for cirrus generation)

MR01 (Nov-Dec 2001)

In the 1st and 3rd periods, air was transported from NH midlatitudes, and TTL was clear.
In the second half, temp. of traj. was low, and air became colder → ineffective for cirrus generation

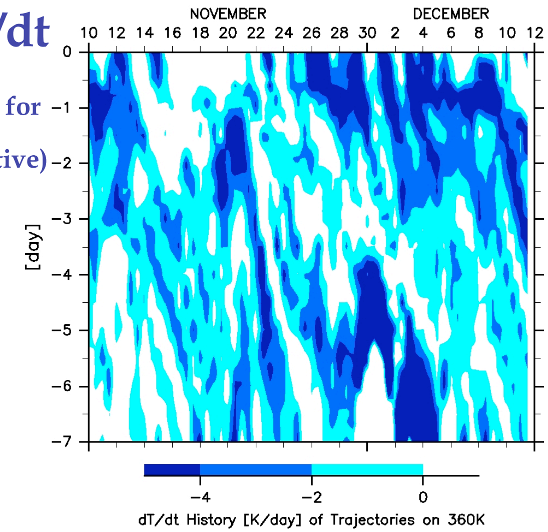


Temp.



dT/dt

(color for negative)



Potential Vorticity Analysis

(Reverse Domain Filling Tech. with 3-day backward traj.)

- +/-2 pvu (10^{-6} K m^2 kg^{-1} s^{-1}) (purple curves) is the indicator of stratospheric air
- Color contours are for average zonal wind distribution.

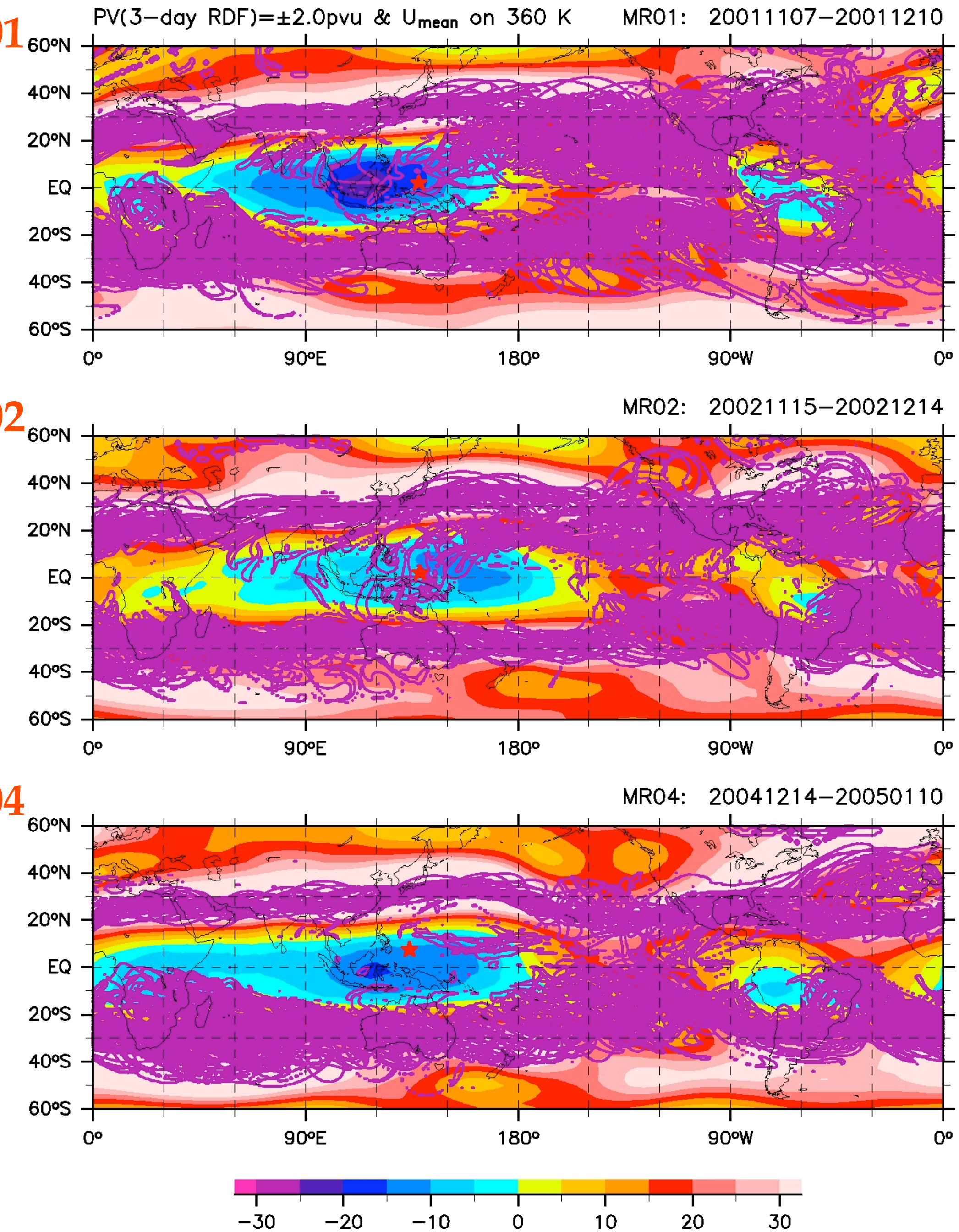
- **MR01: Frequent transports from NH midlatitude LS (compared with MR04) → relatively dry TTL for MR01**

- MR02 is the case where large-amp. Kelvin waves dominated for controlling cirrus variations (We also found that global analysis data do not represent the amplitude of the wave correctly.)

MR01

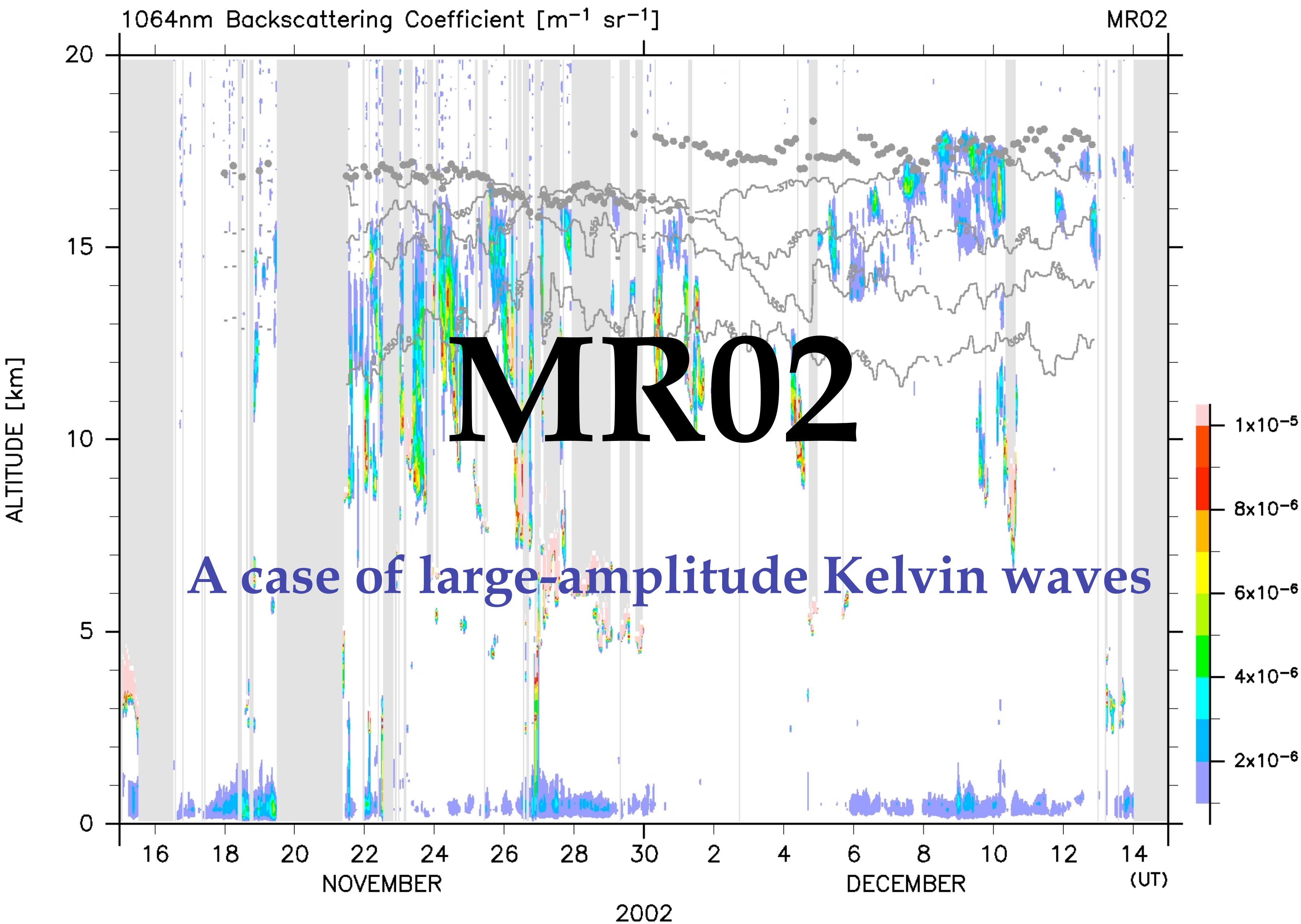
MR02

MR04



MR02

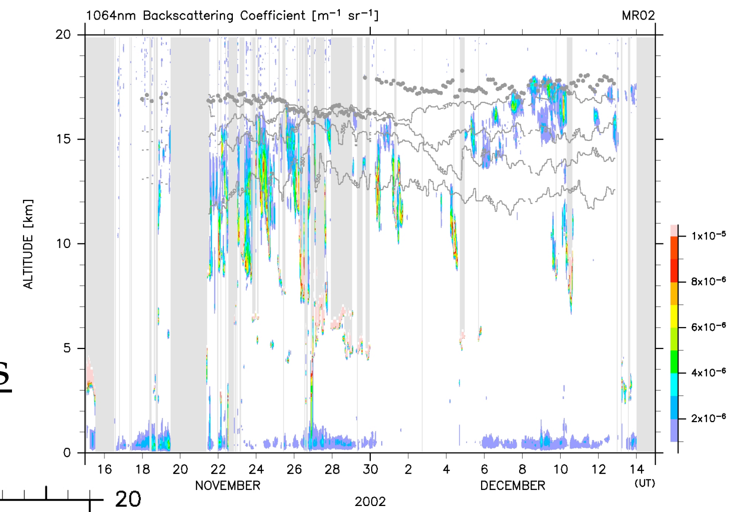
A case of large-amplitude Kelvin waves



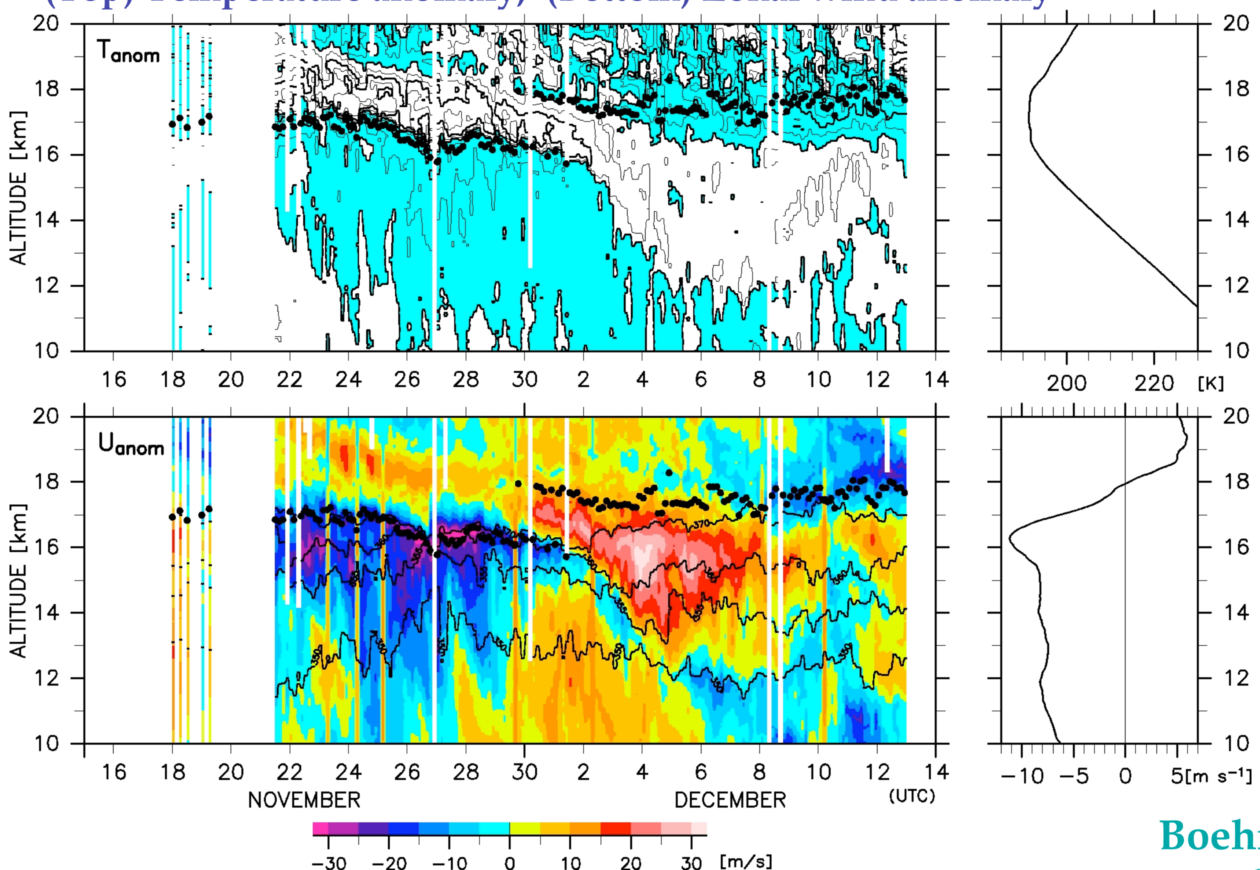
MR02 : Large-Amplitude Kelvin-Wave Case

- Period ~ 22 days
- Background zonal wind ~ -10 m/s at 16 km
- Vertical wavelength ~ 4 km (LS) ~ 8 km (TTL)
- N ~ 2.5 x 10^{-2} s^{-1} (LS), 1.4 x 10^{-2} s^{-1} (TTL)
- Zonal phase speed ~ 8 m/s (from ECMWF)

→ satisfy the linear wave theory of Kelvin waves



(Top) Temperature anomaly, (Bottom) Zonal wind anomaly

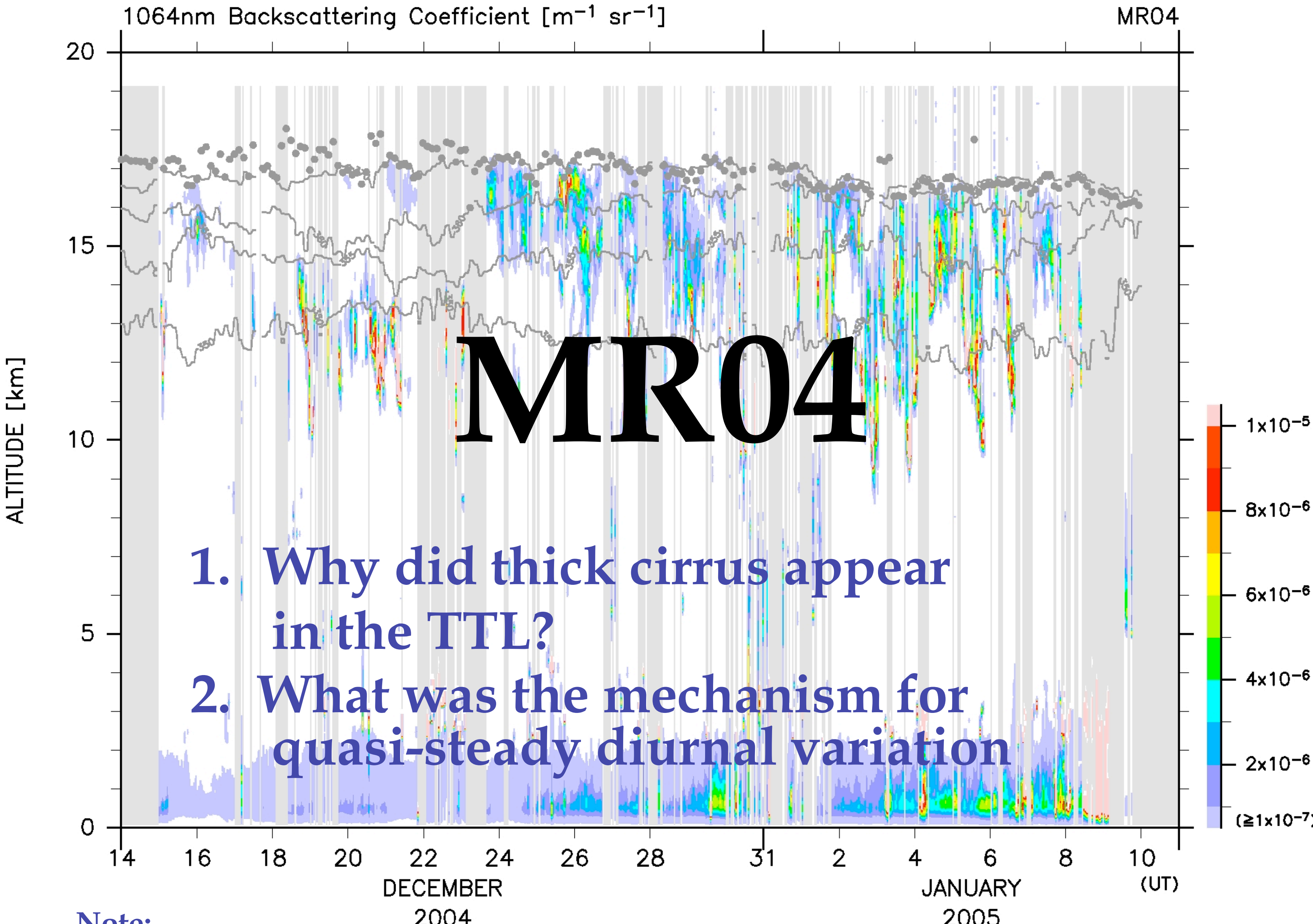


Cirrus appeared in the cold phases of the wave

u′ ~ 30 m/s at 16 km
(→ breaking)

T′ ~ 4 K at 16 km
(max – min = 8 K)

Boehm and Verlinde, GRL, 2000
Immler et al, ACP, 2008 <POSTER>



MR04

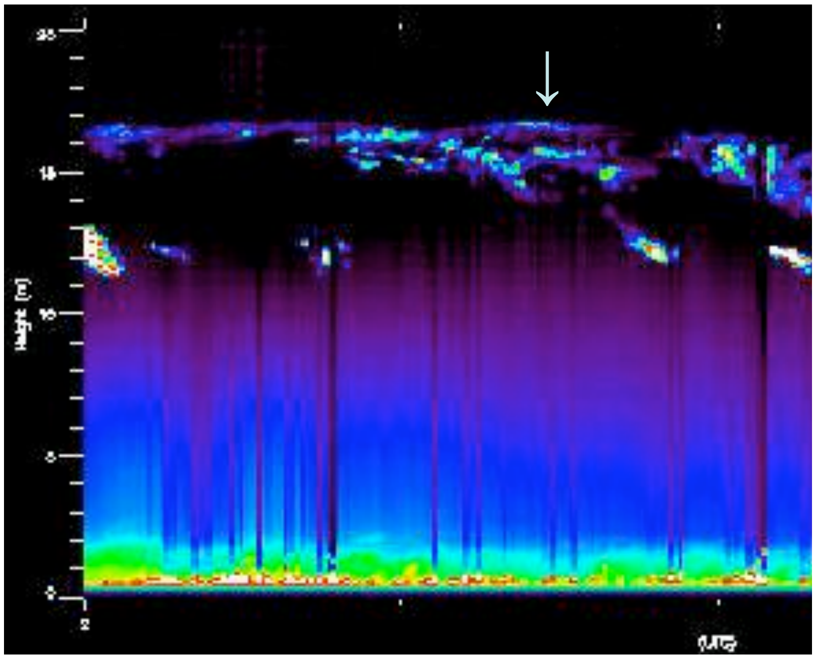
1. Why did thick cirrus appear in the TTL?
2. What was the mechanism for quasi-steady diurnal variation

Note:
PV analysis showed that the midlatitude air did not affect the TTL for MR04.

<u>**MR04 :**</u>

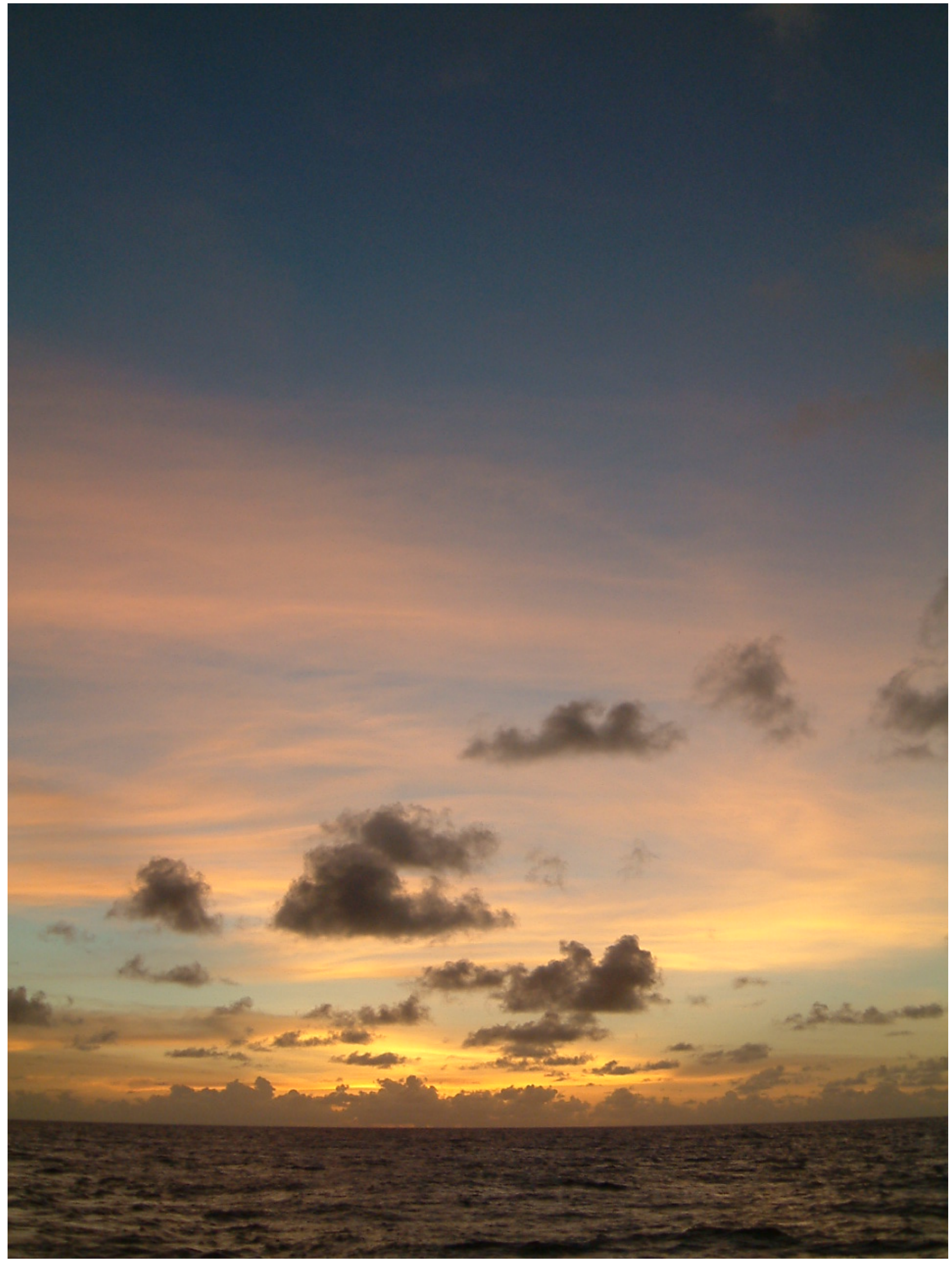
<u>Thick “Visual” TTL Cirrus</u>

Left : Photo taken at 9:16UT (18:16LT), 2 January 2005 (at sunset)
Bottom : Lidar quick look plot during the first half of 2 Jan. (UT)



00UT 06UT 12UT

- We could observe TTL cirrus even during the daytime with polarizing sunglasses
- These are “Visual Clouds” !!
- Optical depths are 0.05~0.1 for the photo



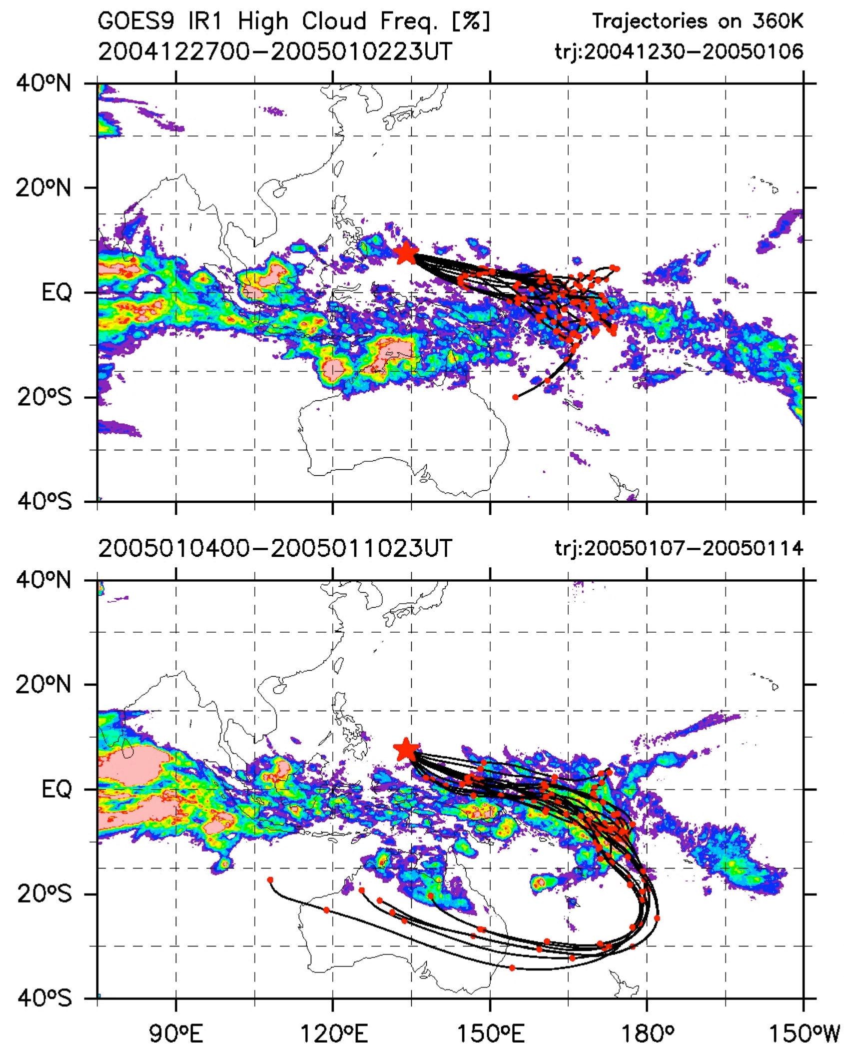
GOES-9 IR1 Tbb Analysis

- GOES-9 Geostationary Sattelite
  (in operation at that time due to
  the termination of GMS-5)
  IR1 Channel : black-body temperature (Tbb)
  0.25x0.25 deg.

- Frequency of Tbb < 210 K
  (deep clouds > ~ 13.5-14 km)
  and Backward Traj. on 360 K
  for late December & for early January

- **Organized clouds moved eastward along Java and the New Guinea islands to the southern tropical western Pacific**

- **Thick, "visual" TTL cirrus over the vessel originated from these organized clouds in the SPCZ region, with 1- or 2-day horizontal transport**



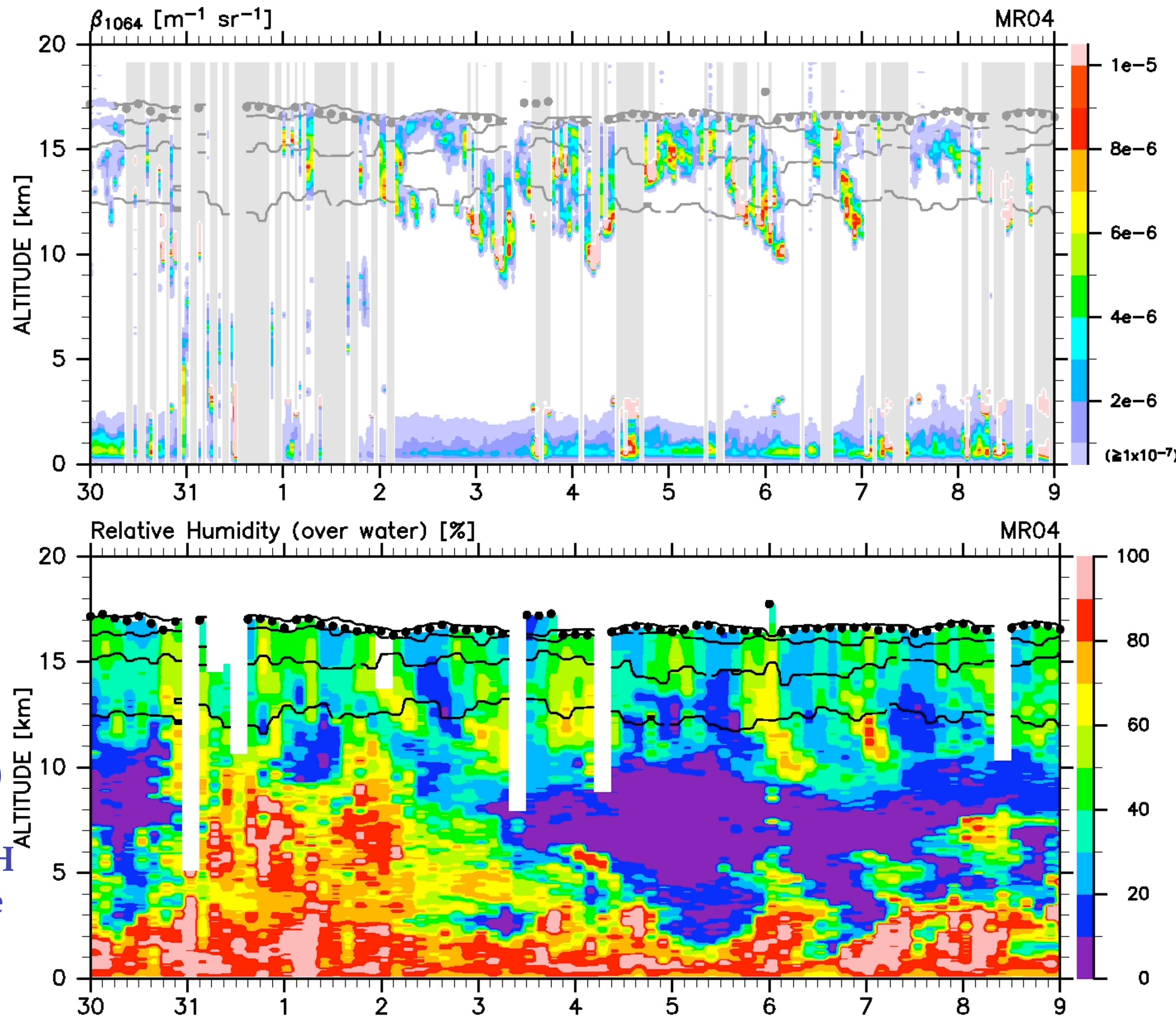
**→ Tropical convective systems generate Kelvin waves and equatorial Rossby waves (i.e., the Matsuno-Gill pattern).
The latter act to transport water to off-equatorial regions in particular phases.**

Diurnal Variations in TTL Cirrus

- **Sedimentation from upper TTL in the evening to 10-12 km in the morning almost everyday**

- **~10 km/day or ~ 10 cm/s (cf. SVC in MR01 descended ~2.6 km/day or ~3 cm/s [Iwasaki et al., GRL, 2004])**

- **Radiosonde (RS92) RH data show clouds and high RH are almost in phase**

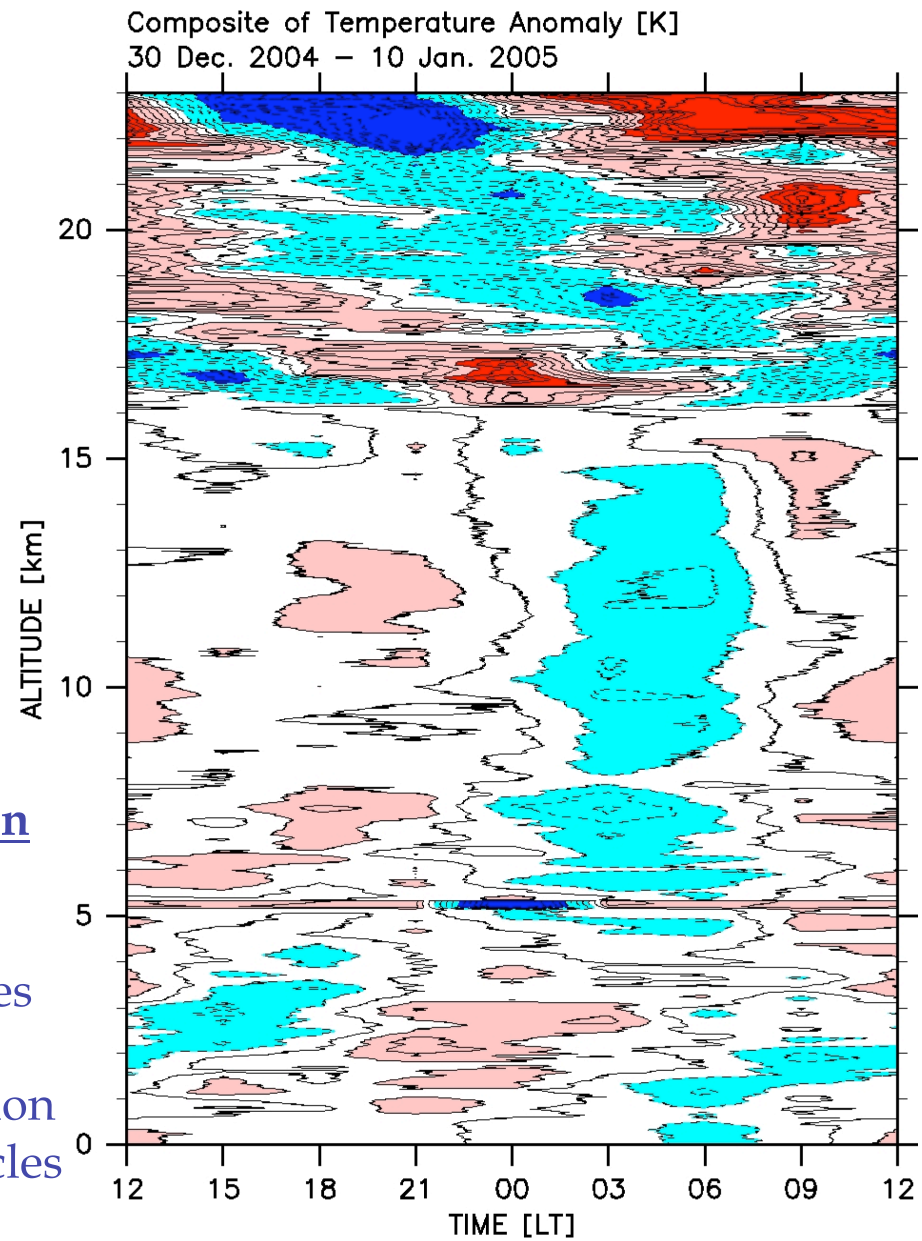


January 2005 (numbers at 00 LT)

Diurnal Variations in Temperature?

3-hourly Vaisala RS92 radiosondes
(Contour interval: 0.2 K
Dark colors for >1 K and <-1 K)

Mid-upper tropo. & Lower strato:
→ Migrating diurnal tide
(GPS analysis by Zeng et al., JGR, 2008)
Tropopause:
→ Amp. > 1 K only during this period
. . . Local disturbances?



Potential Contribution to Cirrus Variation

Daytime:
- T min near TP → cirrus formation
- Warmer lower TTL → evaporates particles

Nighttime:
- T max near TP → prevents cirrus formation
- Colder lower TTL → allows falling particles to be maintained

→ Role of tides (& 24-h GWs) in diurnal vatiations in the TTL cirrus

Conclusions for Cirrus Observations

- Controlling processes for TTL cirrus are:

1. Convective vertical transport of water vapor and cloud particles
2. Horizontal transport (including outflow) of water vapor and cloud particles (associated, e.g., with eq. Rossby waves)
3. Local/regional-scale temperature/vertical-wind variations (associated with Kelvin waves)
4. Dry air transport from midlatitude lower stratosphere

- #4 was important for MR01, #3 was important for MR02, and #3 (late Dec) and #1 & #2 (early Jan) were important for MR04.

- Quasi-steady diurnal variations in TTL cirrus particularly in MR04 → might be an additional factor for determining the TTL dehydration efficiency.

Summary of the Talk

Part I. Ozone obs. in the TTL

(1) Equatorial Kelvin waves

(2) Transport from midlatitude LS

Part II. WV obs. in the TTL

→ "TTL WV MATCH" by Hasebe et al.

Part III. Cirrus obs. in the TTL

- 2001: Dry air transport from midlatitude LS
- 2002: Large-amplitude Kelvin waves
- 2004-5: Convective transport + horizontal transport
  Quasi-steady diurnal variation . . . Role of tides?

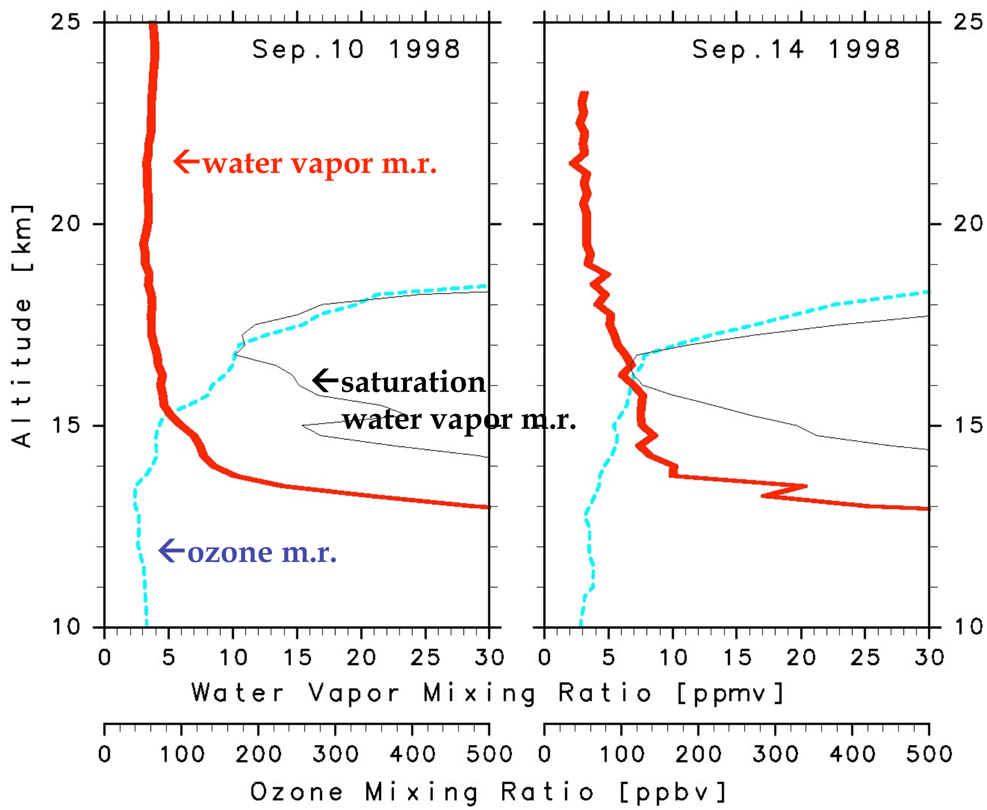
Important role of large-scale meteorology . . . How about cumulonimbus clouds? → Kubokawa et al. <POSTER>

(Global non-hydrostatic model ("NICAM") simulations on the Earth Simulator)

"Dehydration Pump"

NOAA FPH & Ozonesonde soundings at the Galapagos
by the Soundings of Ozone and Water in the Equatorial Region (SOWER)

Downward displacement phase → ozone-rich, dry air into TTL



Upward displacement phase → cold anomaly prevents TTL from excess water

Meteorological data indicate a passage of Kelvin waves

[Fujiwara et al., GRL, 2001]