Numerical Experiments on Formation Processes of Thin Moist Layers in the Tropical Midtroposphere over eastern Pacific

Shigenori Otsuka and Shigeo Yoden (Dept. of Geophysics, Kyoto Univ., Japan)

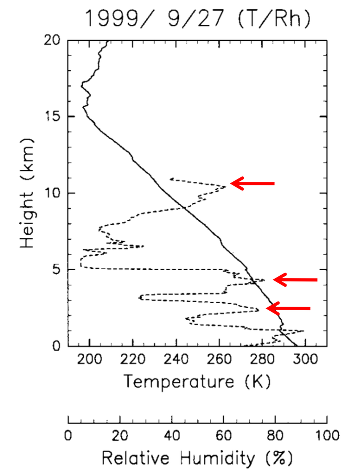
1. Introduction

- Vertically thin layers
  - Reported by radiosondes and airborne observations
    - Right panel: An example over the tropical eastern Pacific (Shiotani et al. 2002)
- Water vapor in the tropics
  - Important for convections and radiation
  - Limited in-situ observations over ocean
- Formation of thin layered structures
  - Study using minor constituents (e.g., Stoller et al. 1999)
  - Case study by numerical experiments (Otsuka and Yoden 2005)

No statistical analysis on formation of the layers

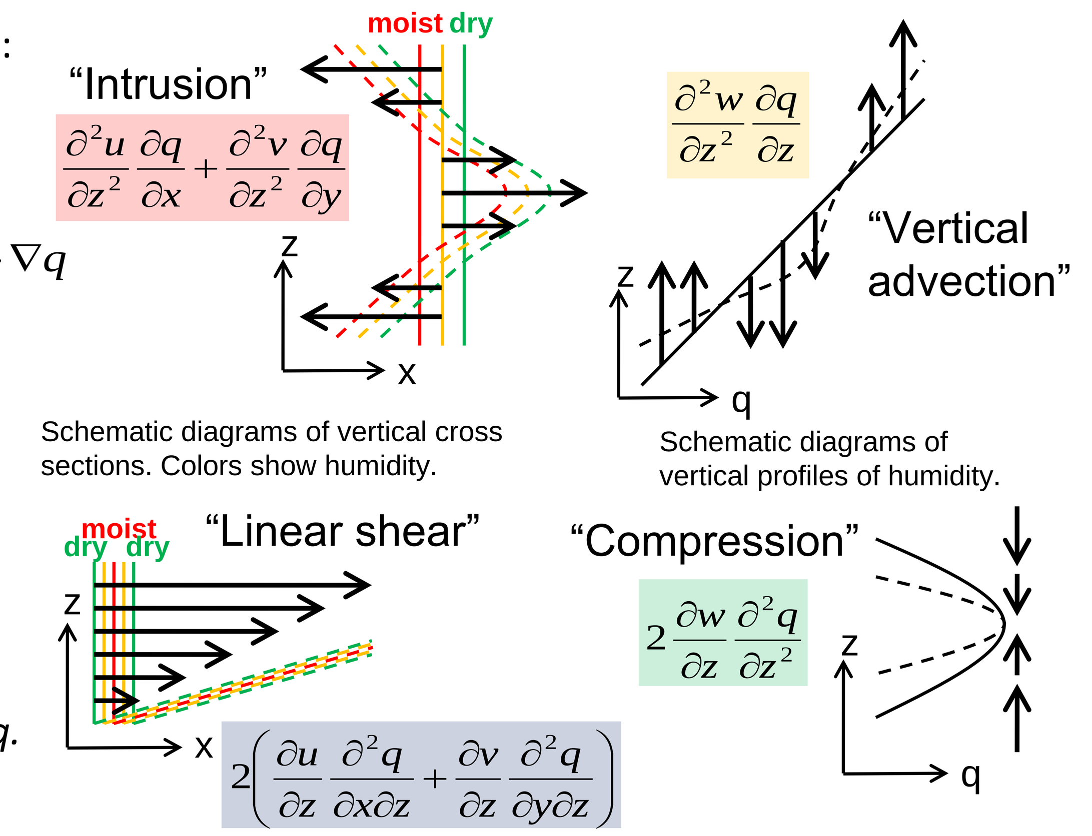
→ the purpose of this study

We focus on moist layers in this presentation.



2. Formation of moist layers by advection

- Necessary condition at the central altitude of the layers:
  $$\frac{\partial^2 q}{\partial z^2} < 0$$
- When "q" is a passive tracer,
  $$0 = \frac{\partial^2}{\partial z^2}\left(\frac{Dq}{Dt}\right) = \frac{D}{Dt}\left(\frac{\partial^2 q}{\partial z^2}\right) + 2\frac{\partial \mathbf{u}}{\partial z}\cdot\nabla\left(\frac{\partial q}{\partial z}\right) + \frac{\partial^2 \mathbf{u}}{\partial z^2}\cdot\nabla q$$
- Thus,
  $$\frac{D}{Dt}\left(\frac{\partial^2 q}{\partial z^2}\right) = -\left(\frac{\partial^2 u}{\partial z^2}\frac{\partial q}{\partial x} + \frac{\partial^2 v}{\partial z^2}\frac{\partial q}{\partial y}\right) - \left(\frac{\partial^2 w}{\partial z^2}\frac{\partial q}{\partial z}\right) - 2\left(\frac{\partial u}{\partial z}\frac{\partial^2 q}{\partial x\partial z} + \frac{\partial v}{\partial z}\frac{\partial^2 q}{\partial y\partial z}\right) - 2\frac{\partial w}{\partial z}\frac{\partial^2 q}{\partial z^2}$$
- A layer can be formed if the value above is negative.
- We used relative humidity (RH) instead of mixing ratio q.



Schematic diagrams of vertical cross sections. Colors show humidity.

Schematic diagrams of vertical profiles of humidity.

Source terms in RH

$$\frac{D}{Dt}\left(\frac{\partial^2 \mathrm{RH}}{\partial z^2}\right) \simeq S_1 + S_2 + S_3 + S_4 + S_q + S_\theta + S_p,$$

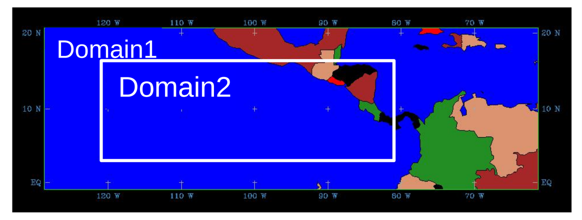
$$S_1 \equiv -\left(\frac{\partial^2 u}{\partial z^2}\frac{\partial \mathrm{RH}}{\partial x} + \frac{\partial^2 v}{\partial z^2}\frac{\partial \mathrm{RH}}{\partial y}\right),$$
$$S_2 \equiv -\frac{\partial^2 w}{\partial z^2}\frac{\partial \mathrm{RH}}{\partial z},$$
$$S_3 \equiv -2\left(\frac{\partial u}{\partial z}\frac{\partial^2 \mathrm{RH}}{\partial x\partial z} + \frac{\partial v}{\partial z}\frac{\partial^2 \mathrm{RH}}{\partial y\partial z}\right),$$
$$S_4 \equiv -2\frac{\partial w}{\partial z}\frac{\partial^2 \mathrm{RH}}{\partial z^2},$$
$$S_q \equiv \frac{\partial^2}{\partial z^2}\left(\frac{\mathrm{RH}}{q}\frac{Dq}{Dt}\right),$$
$$S_\theta \equiv -\frac{\partial^2}{\partial z^2}\left(\frac{\mathrm{RH}}{e_s}\frac{de_s}{dT}\frac{T}{\theta}\frac{D\theta}{Dt}\right),$$
$$S_p \equiv \frac{\partial^2}{\partial z^2}\left(\mathrm{RH}\left(1 - \frac{T}{e_s}\frac{de_s}{dT}\frac{R}{c_p}\right)\frac{1}{p}\frac{Dp}{Dt}\right).$$

T: temperature, θ: potential temperature, c_p: specific heat at constant pressure, e_s: saturated vapor pressure of water

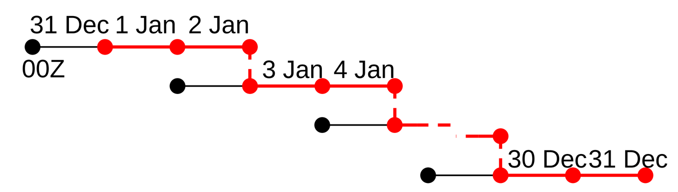
3. Model description

- NCAR/PSU MM5 Version 3.6.2
- 2-way nesting
- Input: NCEP Final Analyses (1° × 1°)
- 62 levels from surface to 10 hPa

	Domain1	Domain2
Horizontal grid (dx)	63 km	21 km
Num of grid	40 × 120	73 × 211
Cumulus scheme	Anthes-Kuo	Grell
Time interval (dt)	60 s	20 s



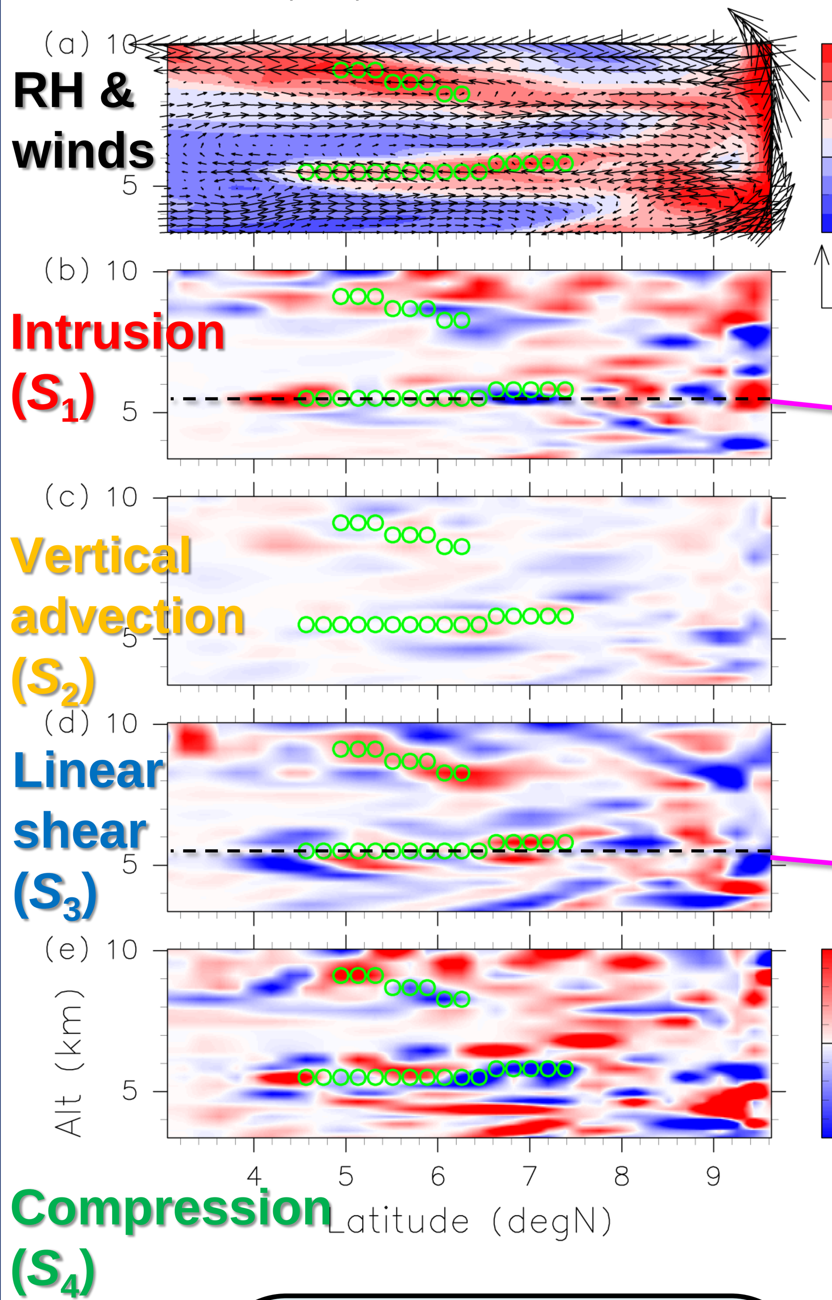
- Case 1:
  - Calculation period: 3.5 days 26 Sep 1999 00Z – 29 Sep 1999 12Z
  - See Otsuka and Yoden (2005)
- Case 2:
  - Calculation period: 2 years 1 Jan 2005 – 31 Dec 2006
  - 3-day integrations with one day overlapping to discard initial one day
  - See Otsuka and Yoden (2009)



4. Case 1 (26-29 Sep 1999)

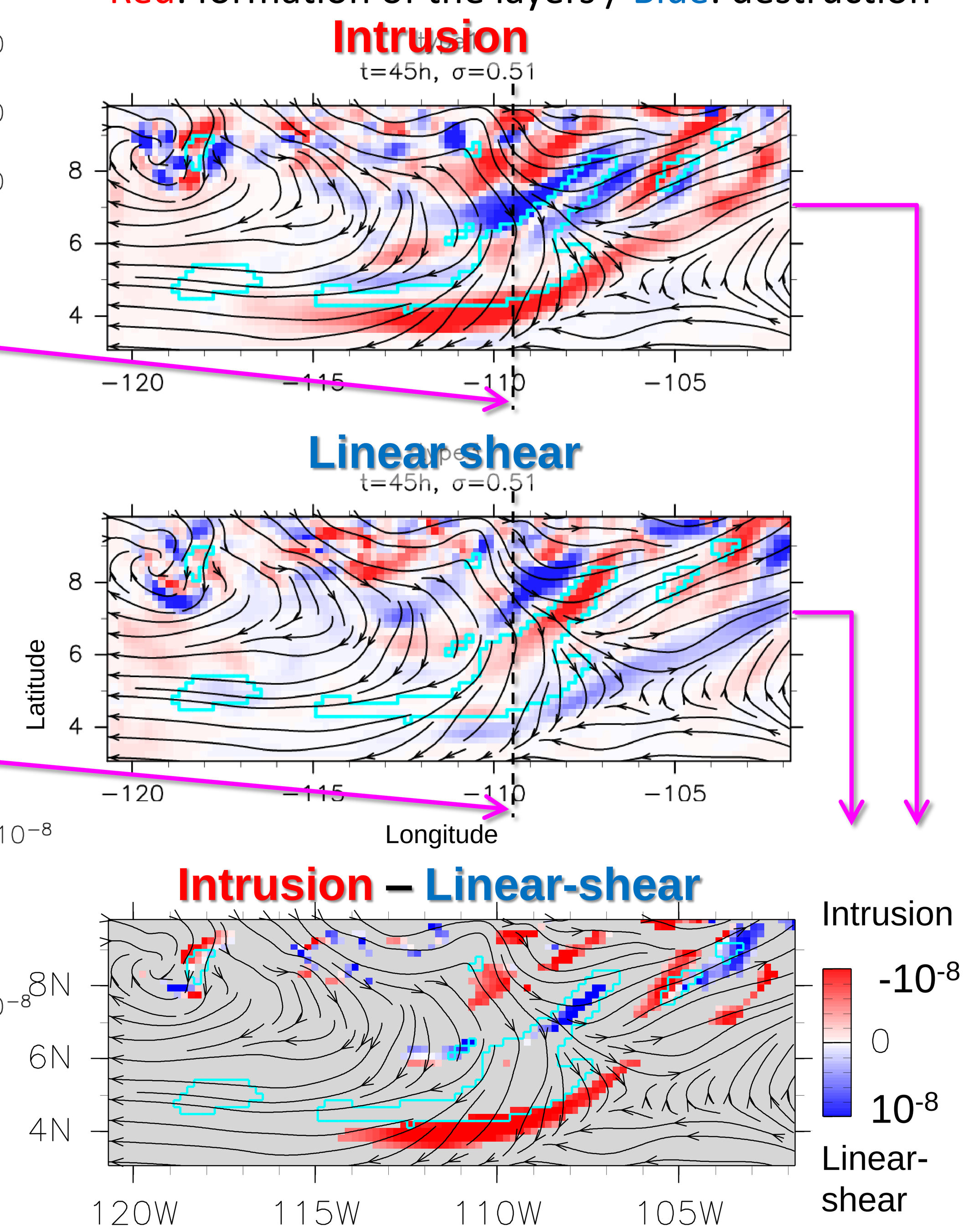
Latitude-height cross sections of RH, winds, and the source terms

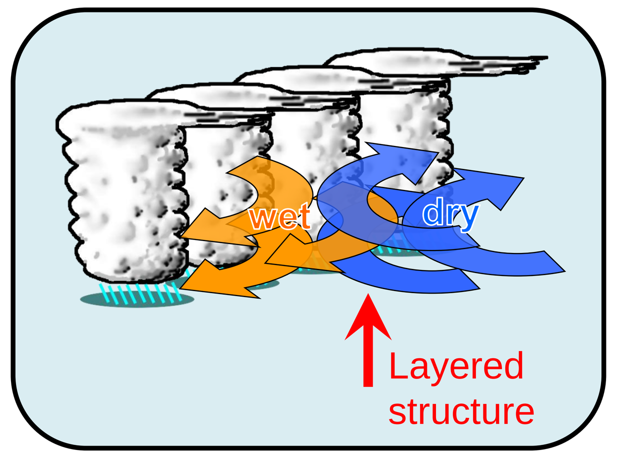
Green circles: center of the thin moist layers detected with the definition of Otsuka and Yoden (2009) with δRH = 35% and δh = 2km.



Horizontal distribution of the source terms, Streamlines, and the thin moist layers

- t = 45 h (27 September 1999 21:00 UTC)
- σ = 0.51 (z ∼ 5 km)
- Red: formation of the layers / Blue: destruction



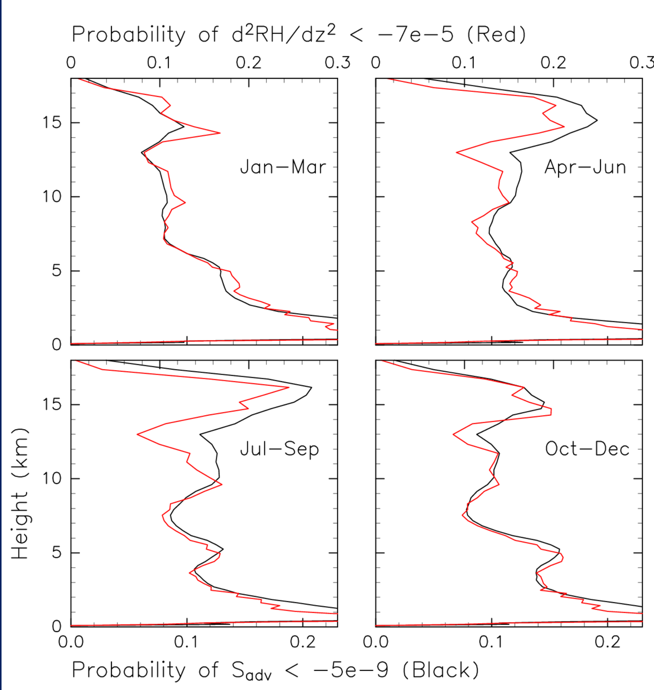


Schematic image of the shear flow in this case.

- Layers at σ=0.51 (∼5 km)
- Gray: intrusion term + linear-shear term > -5 × 10^{-9} % m^{-2} s^{-1} (layers are not growing in these regions)
- Red/Blue: intrusion term – linear-shear term
- The result is consistent with that shown by Otsuka and Yoden (2005)

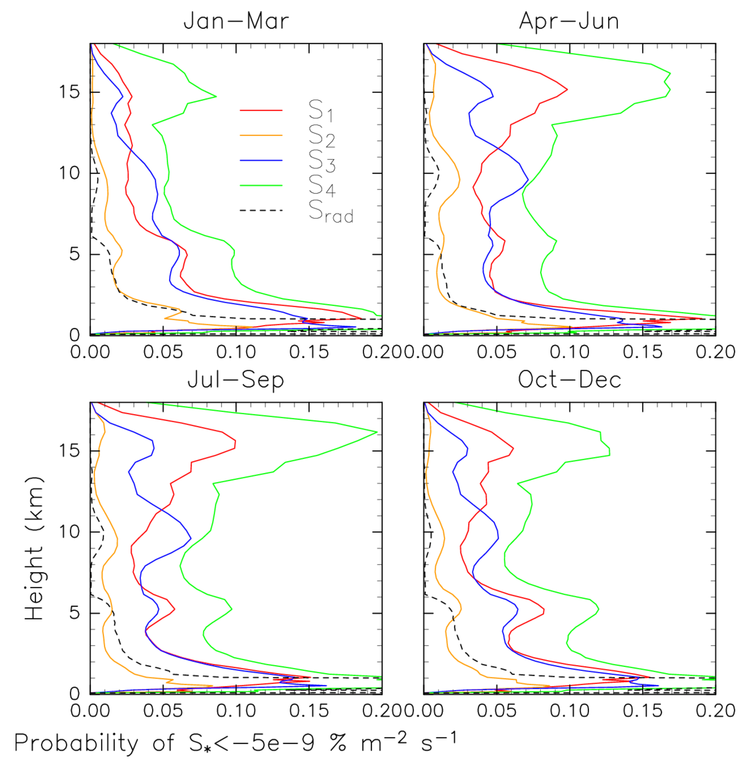
5. Case 2 (statistics in 2005-2006)

Frequency of extreme values for ∂²RH/∂z² and sum of the source terms

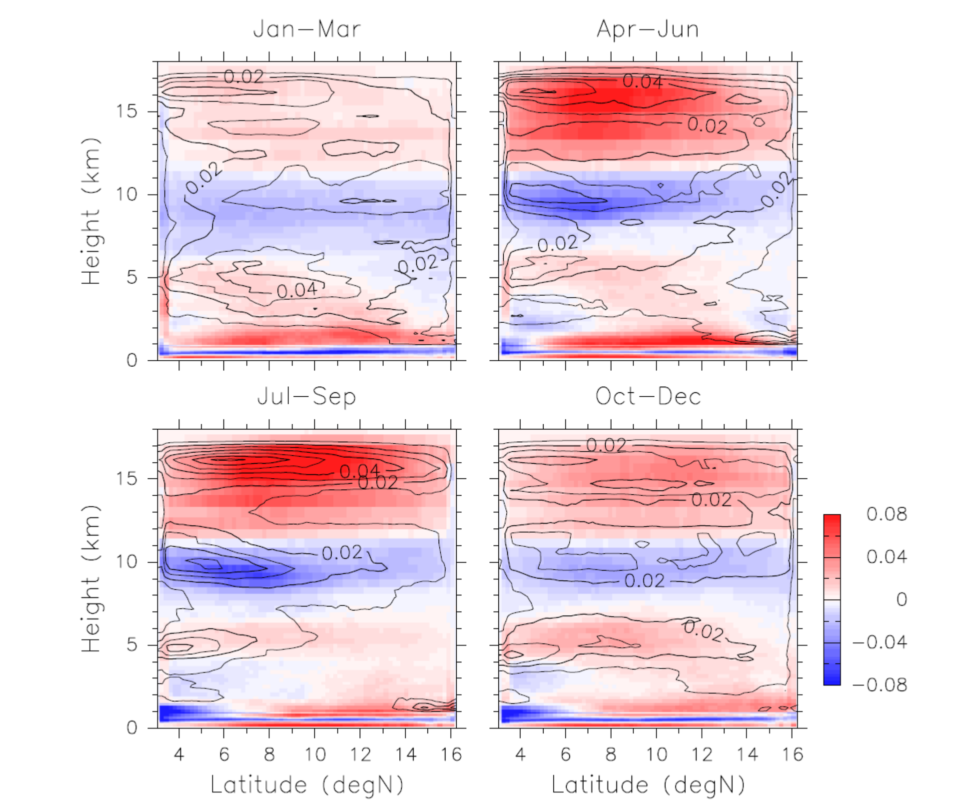


- ∂²RH/∂z²
  - Threshold: -7x10^{-5} % m^{-2}
  - This value corresponds to a layer with the RH difference of 35% and the thickness of 2 km.
- Sum of 4 source terms
  - Threshold: -5x10^{-9} % m^{-2} s^{-1}
- Vertical distribution
- Each season
- Consistent with each other
  - This analysis method works well
- Excess of source terms in the upper troposphere in boreal summer
  - Gravity waves?

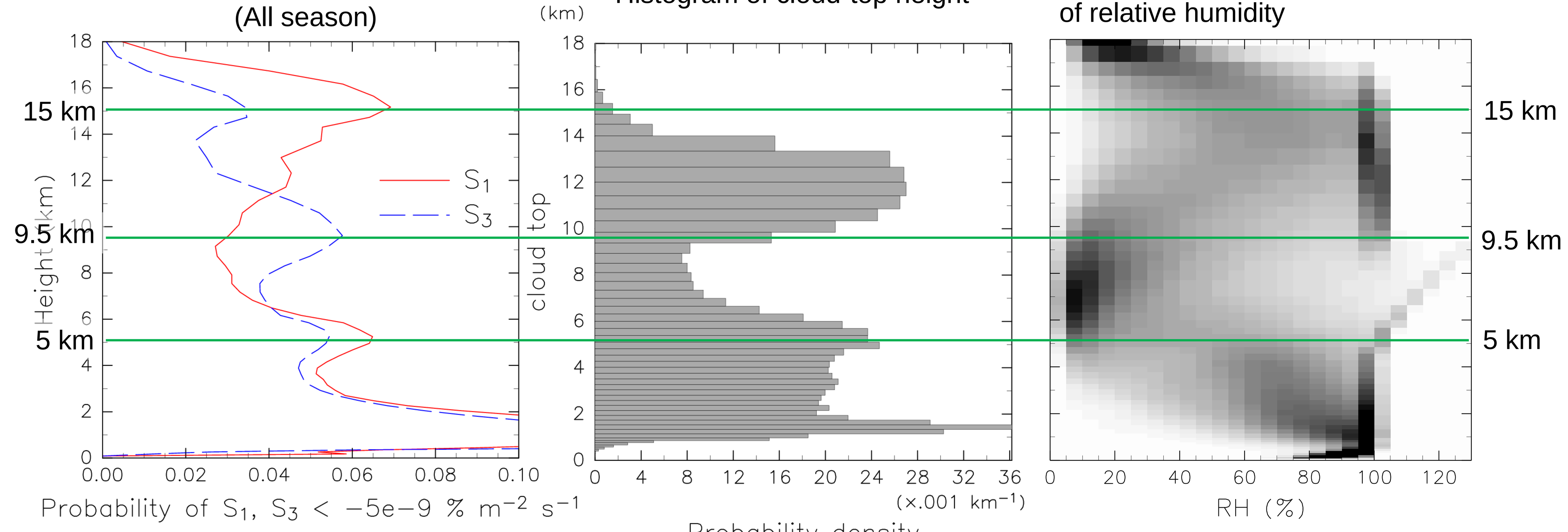
Frequency of extreme values of source terms



- Threshold: -5x10^{-9} % m^{-2} s^{-1}
- Vertical distribution
- Each season
- Compression term contains wavy motions.
- Vertical-advection term and radiation term (S_θ) are not dominant.



Latitude-height cross sections of the frequency of S_1 < -5 × 10^{-9} % m^{-2} s^{-1} minus the frequency of S_3 < -5 × 10^{-9} % m^{-2} s^{-1}. Dependency on latitude is small. Contours show the occurrence ratio of the thin moist layers detected with δRH > 35% and δh < 2 km.



Three local maxima: 5 km (S_1, S_3), 9.5 km (S_3), and 15 km (S_1, S_3).

The peak of S_1, S_3 at 5 km corresponds to the peak of the cloud-top height, whereas other two peaks of S_1, S_3 correspond to the top and the bottom of the cloudy levels in the upper troposphere.

Three local maxima of the source terms correspond to the transition altitudes from the dry levels to the moist levels.

6. Summary

- Diagnosis on formation of thin moist layers
  - Formation of the layers by advection is classified to four types
  - Formation of new layers: Intrusion and Linear-shear
  - Enhancement and maintainance: compression
- Application to the numerical experiments over equatorial eastern Pacific
  - Intrusion: dominant at 5 and 15 km in altitude
  - Linear-shear: dominant at 5 and 9.5 km in altitude
  - Detrainment from cumulus convections and the distribution of water vapor may be responsible.

- References:
  - Otsuka and Yoden, 2005: *SOLA*, **1**, 69—72.
  - Otsuka and Yoden, 2009: *J. Climate*, **22**, 5102—5114.