Numerical Modeling of Moist Convection in Jupiter's Atmosphere

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Introduction

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- The mean structure of the cloud layer in Jupiter's atmosphere is thought to be maintained by the statistical contribution of a large number of clouds driven by internal and radiative heating/cooling over multiple cloud life cycles.
- However, the mean structure and its relationship to cloud convection has not been clarified yet.
  - The thick visible clouds prevent the vertical structure of the entire cloud layer to be observed by remote sensing.
  - Galileo probe's entry site is one of hot spots which are cloudless region.
  - Several cloud resolving models are developed, but most of the models have been used to simulate an onset and initial expanding phase of a single cloud under a simplified and arbitrary initial condition (i.e., Yair et al., 1992, 1995; Hueso and Sanchez-Lavega, 2001).

Introduction

- The mean vertical profiles of the atmosphere have been illustrated by the results obtained using one-dimensional equilibrium cloud condensation models (ECCM)
  - Weidenschilling and Lewis (1973)
  - Atreya and Romani (1985)

- But, Atmospheric dynamics and cloud physical processes would modify the features obtained by ECCM.

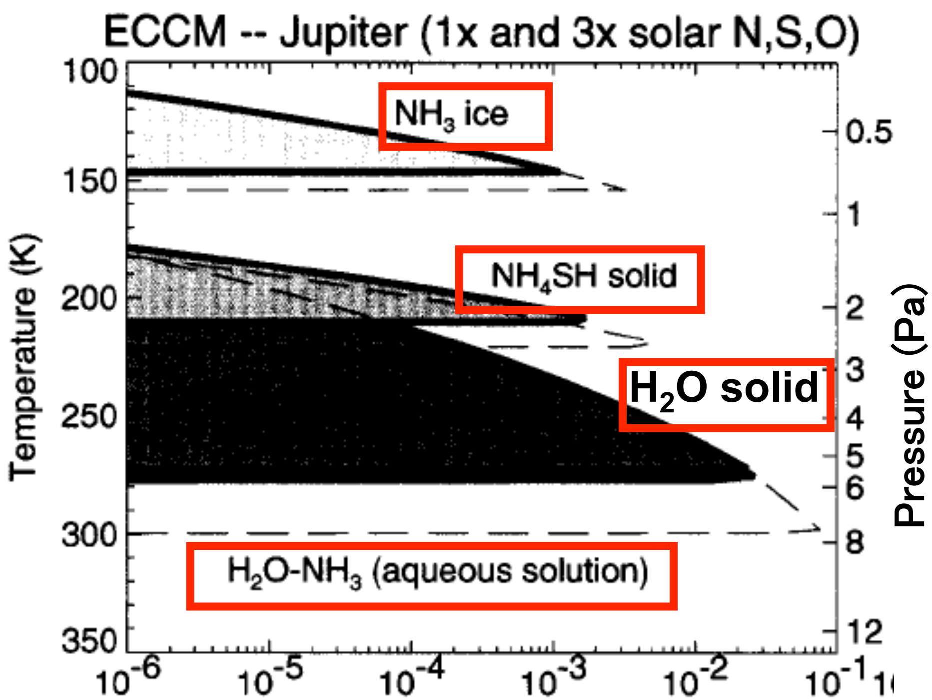


Fig. Vertical structure of Jupiter's cloud obtained by the equilibrium cloud condensation model (Atreya *et al*, 1999).

Three Cloud layers!

Toward a direct simulation

- We have been developing two-dimensional numerical models of cloud convection that incorporates phase change and cloud microphysics in order to investigate the average structure of the cloud layer that is established through a large number of life cycles of convective clouds.
  - Nakajima et al. (2000) [consider H_2O only]
  - Sugiyama et al. (2009) [consider three condensible species]

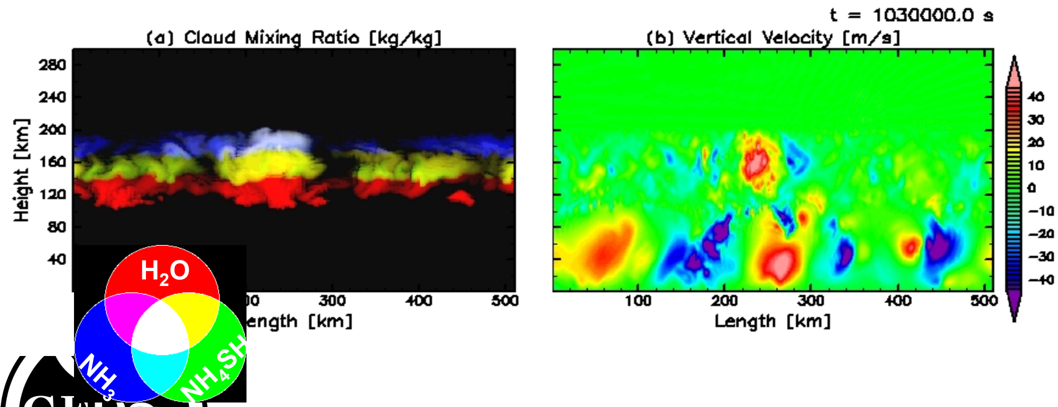


Fig: The preliminary results of numerical simulation by Sugiyama *et al*. (2009). Distribution of cloud mixing ratio (left) and vertical velocity (right).
The mixing ratios of H_2O ice, NH_4SH ice, and NH_3 ice are represented using red, green, and blue color tones, respectively, and that of multiple composition cloud is represented by a superposed plot of the three colors.

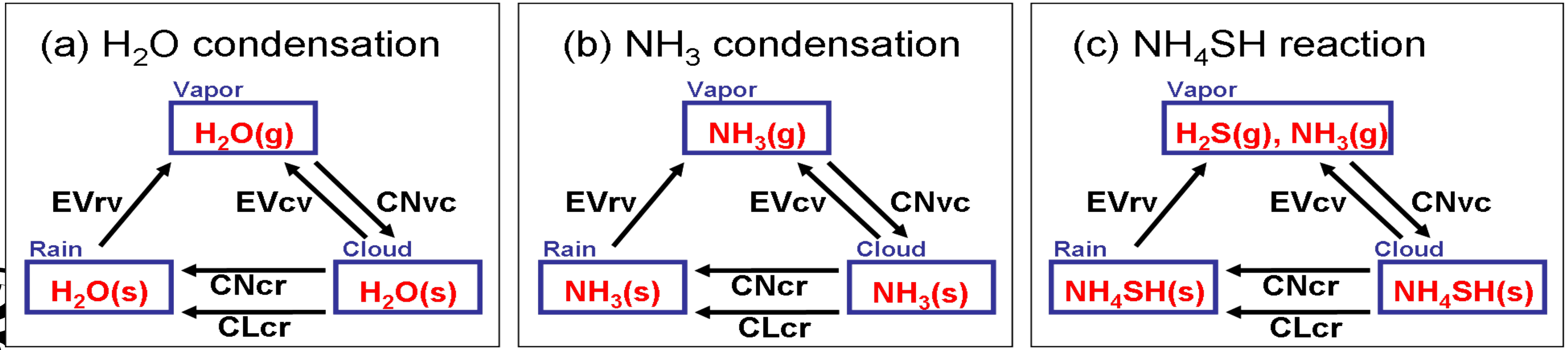
Our purpose

- In order to investigate idealistic characteristics of convective motion and mean vertical structure of the cloud layer, we perform a long-time numerical simulation of a two-dimensional cloud convection model.

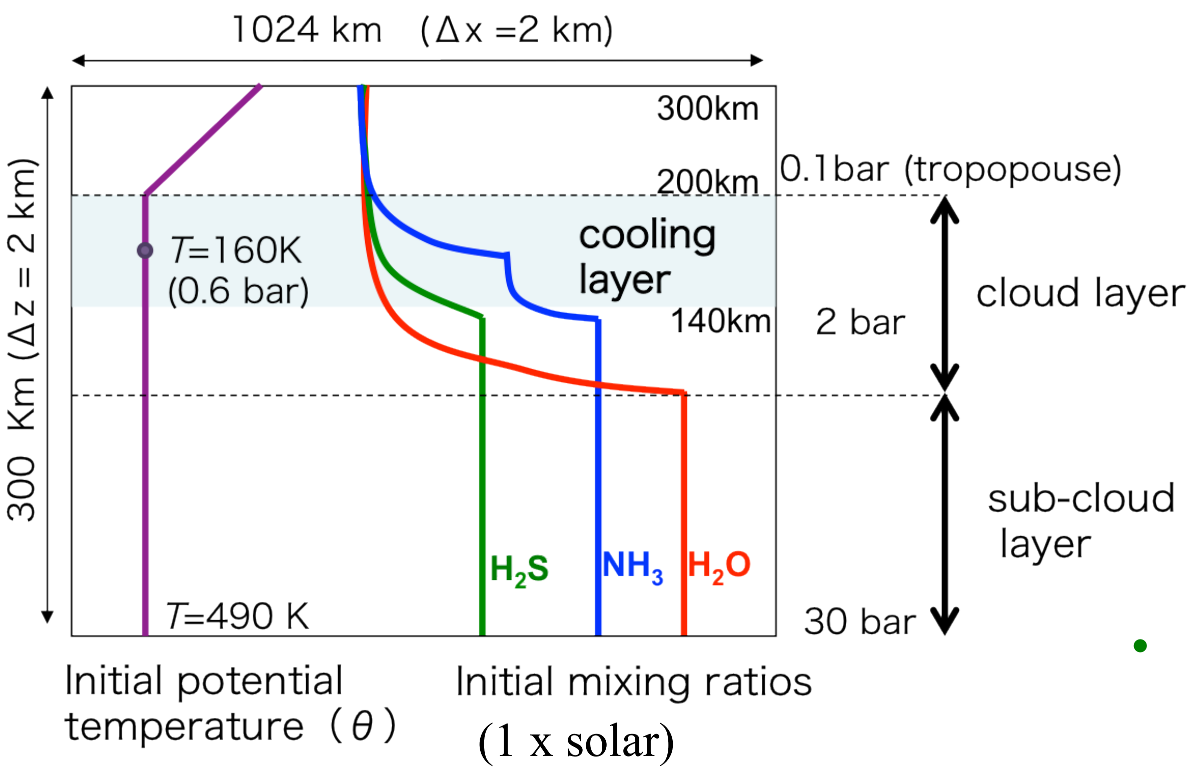
Model description

Numerical model

- Two-dimensional numerical fluid model based on the quasi-compressible system (Klemp and Wilhelmson, 1978)
  - The system consists of the equations of motion, continuity and thermodynamic and conservation equations of condensible species.
    - Radiation transfer process: Thermal forcing given as a substitute for radiative cooling.
    - Cloud microphysics process: The parameterization schemes of Kessler (1969) that is well-used in Earth's atmospheric simulation is used.



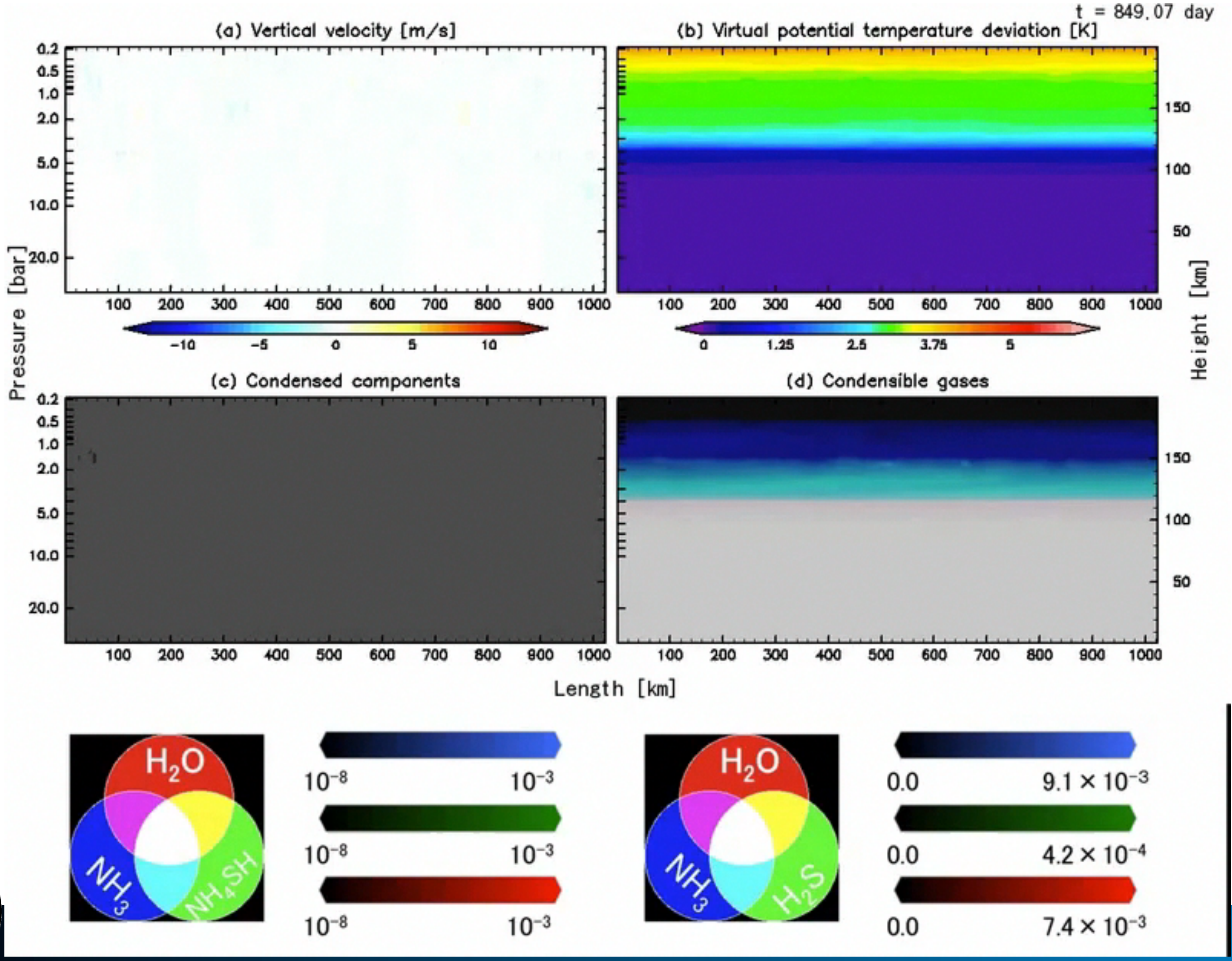
Set-up of the experiments



- Boundary conditions
  - Horizontal boundary is cyclic. Stress free condition and $w = 0$ are given at the lower and upper boundaries.
  - Temperature and mixing ratios of vapor at the lowest level are fixed.
- Initial condition
  - Random potential temperature perturbation ($\Delta\theta_{max} = 0.1$ K) is given to seed convective motion.

Results

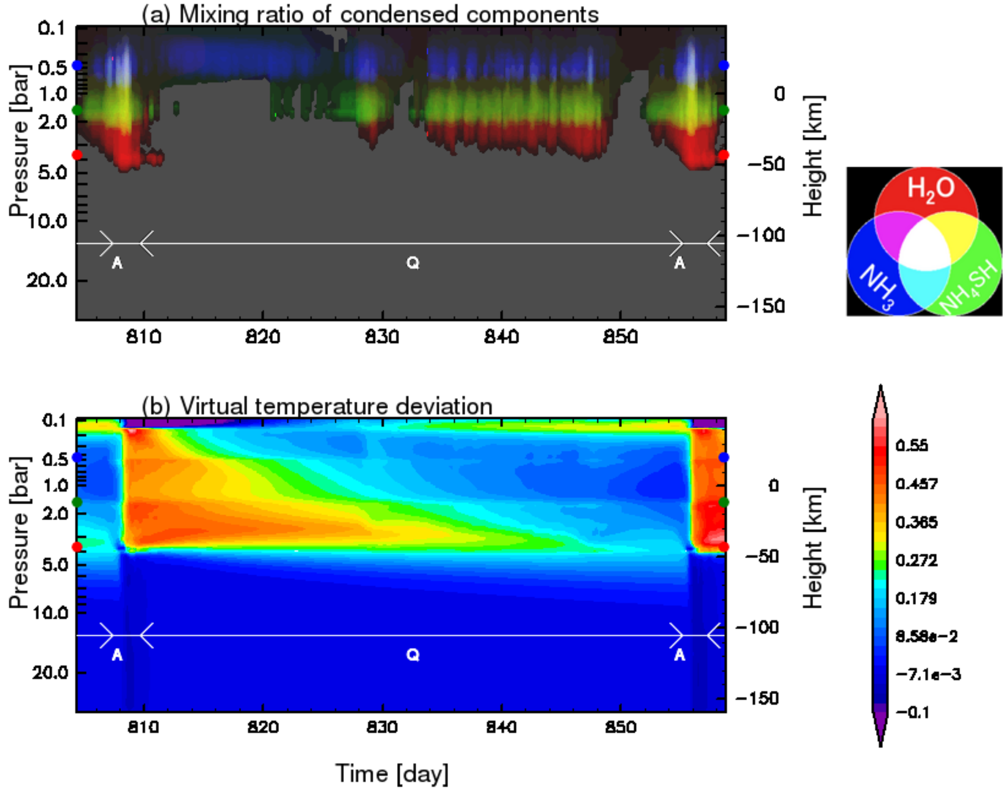
Results: Animation



Temporal variation

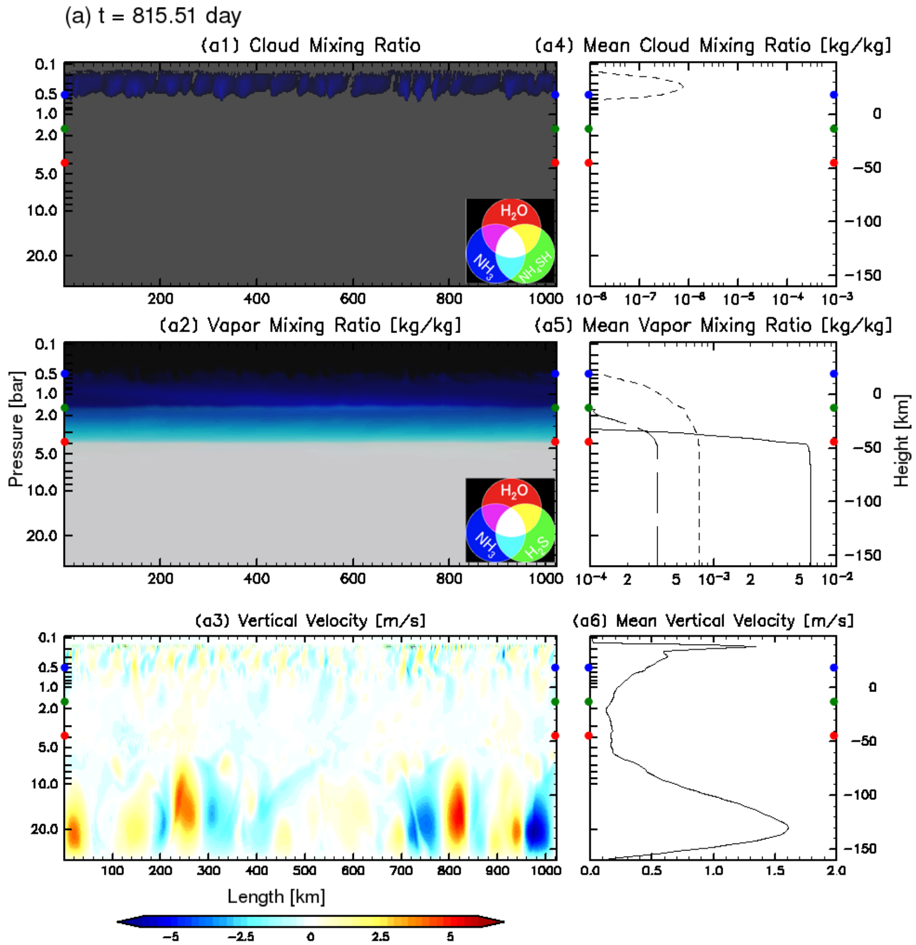
- The convective activity of the whole layer is not steady but quasi-periodic with a period of about 40~50 days.

- Overall temperature of the cloud layer synchronizes with the intermittent convective activity.
  - We will refer the time when the active cloud convection occurs as `active period' (A) and the other as `quiet period' (Q).



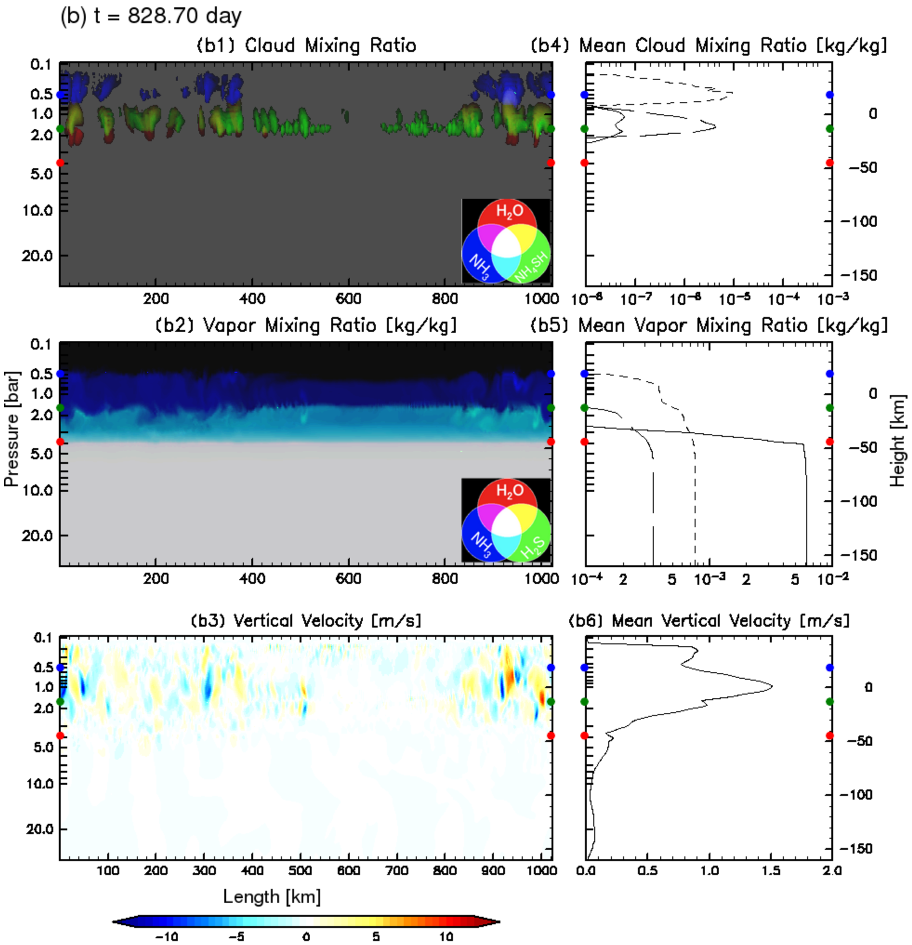
Quiet period: over view (1)

- At the beginning of this quiet period, the NH_3 clouds are distributed horizontally.
  - Vertical motion is weak ($w = \sim 5$ m/s)
- The vertical motion in the sub-cloud layer is the remnant of convective motion driven during an active period.



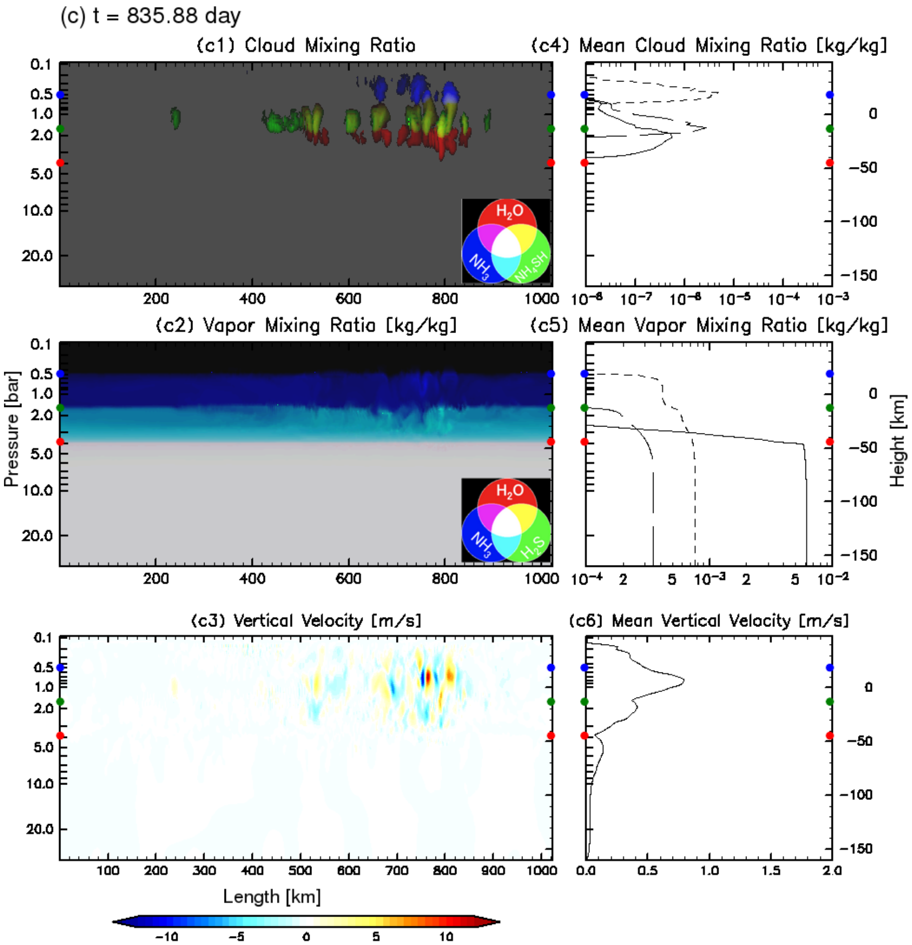
Quiet period: over view (2)

- As time progress, NH_4SH clouds develop.
- Mixing of different condensible gases and condensed components across the NH_3 LCL or NH_4SH LCL is weak, but occurs occasionally due to the upward or downward penetration of convective plumes.
  - We will refer the “lifting condensation level” as LCL



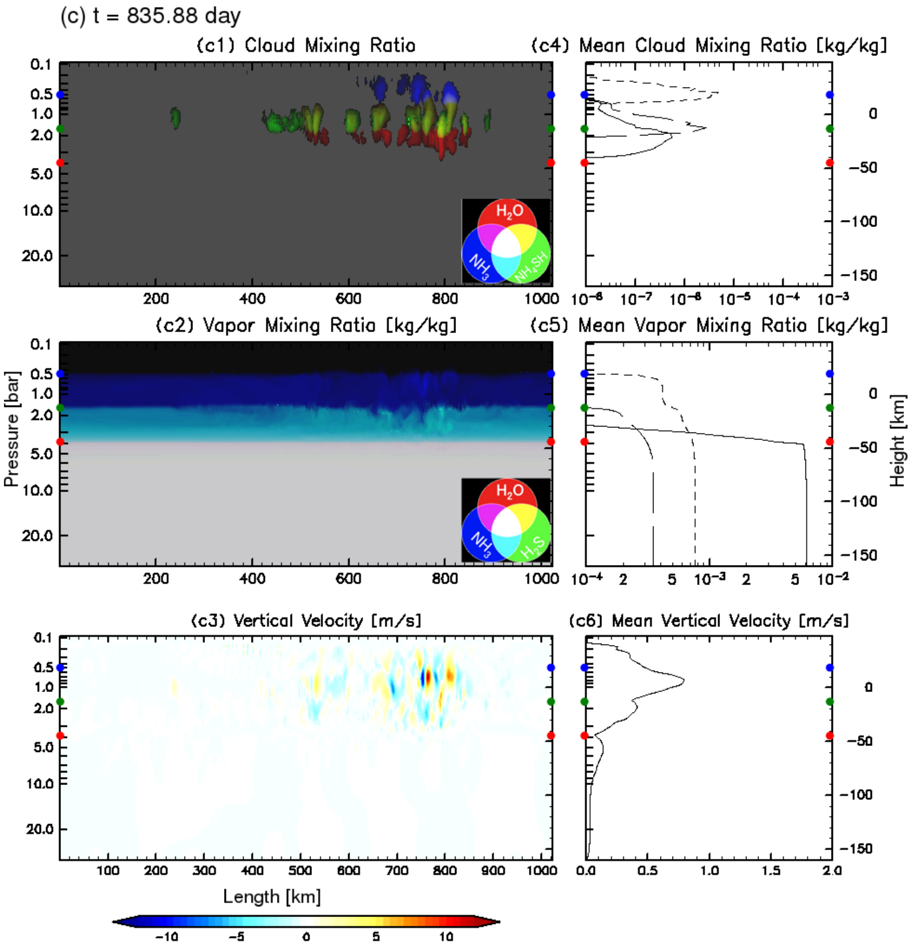
Quiet period: over view (3)

- Following the onset of NH_4SH clouds, H_2O clouds begin to form locally.
- Mixing of different condensible gases and condensed components across the NH_3 LCL or NH_4SH LCL is still weak.



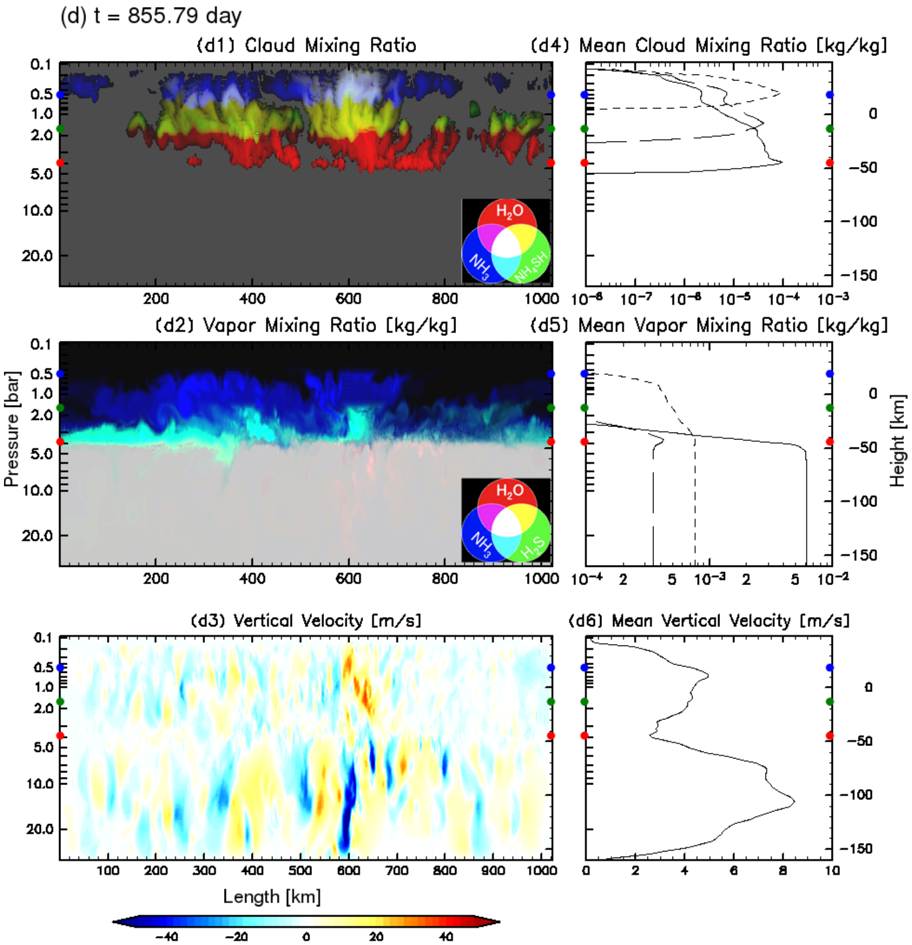
Characteristic of vertical motion

- NH_3 LCL acts as a kinematic and compositional boundary, as does the NH_4SH LCL to a lesser degree.
  - The horizontal-mean mixing ratio of NH_3 gas tends to be constant between NH_4SH LCL and NH_3 LCL.
  - The vertical profile of $\sqrt{\overline{w^2}}$ has local minimum or inflection points at the NH3 LCL and NH4SH LCL.



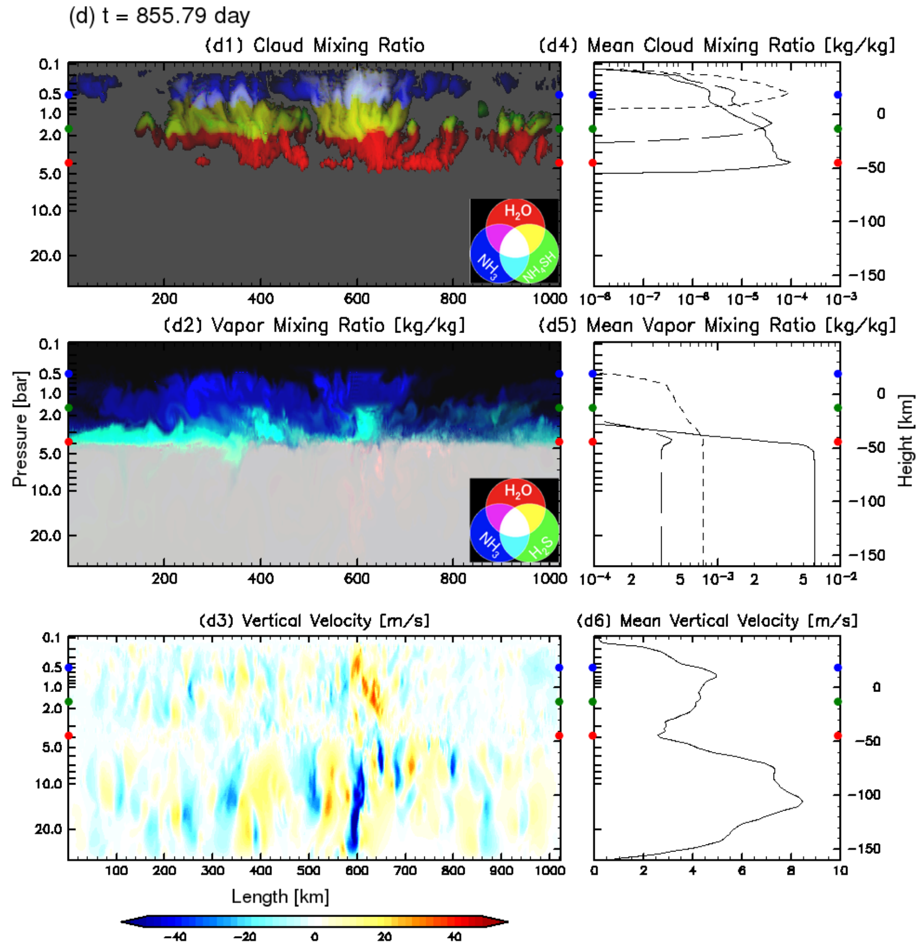
Active period: over view

- Vigorous cumulonimbus clouds develop.
- Narrow, strong, cloudy updrafts in the cloud layer ($w \sim$ 50 m/s)
  - Wide, weak, dry downdrafts ($w \sim$ 10 m/s).
- Considerable amounts of H_2O and NH_4SH condensates are transported to the tropopause.
- Due to the vigorous vertical transport, the mixing ratio of each condensible gases is highly inhomogeneous.



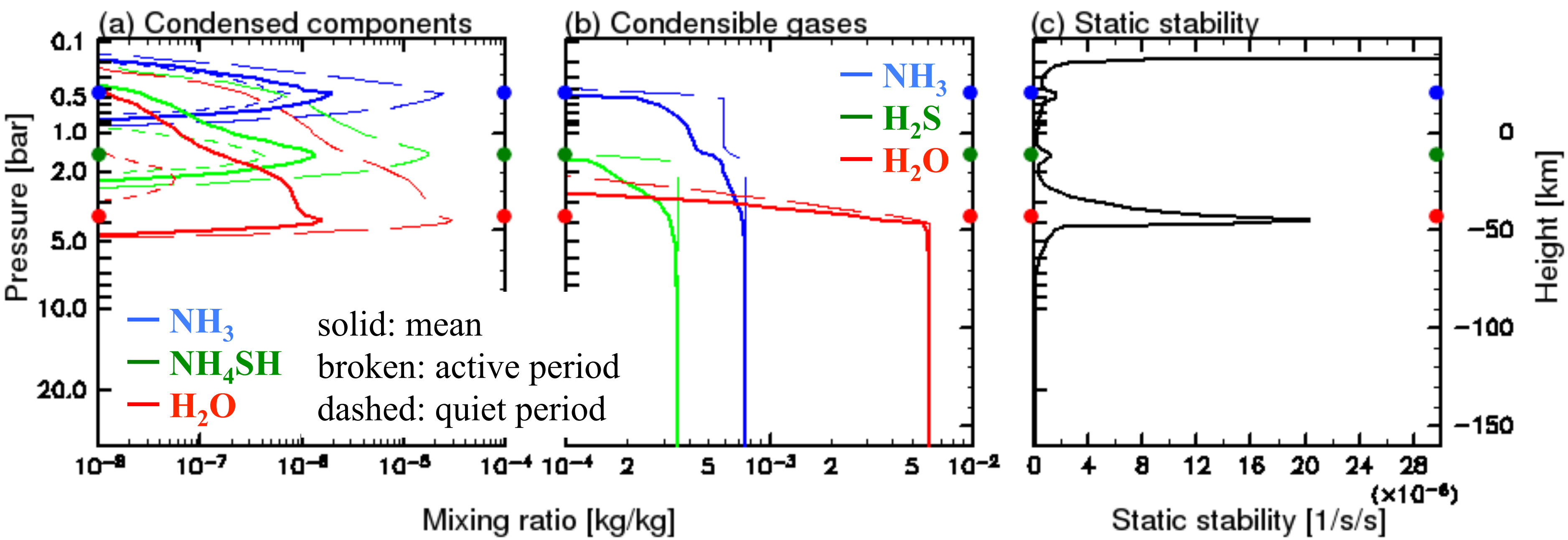
Characteristic of vertical motion

- H_2O condensation level acts as a kinematic and compositional boundary.
  - The horizontal-mean mixing ratios of all condensible gases decrease with height from the H_2O condensation level.
  - The vertical profiles of $\sqrt{\overline{w^2}}$ has local minimum at the H_2O condensation level.



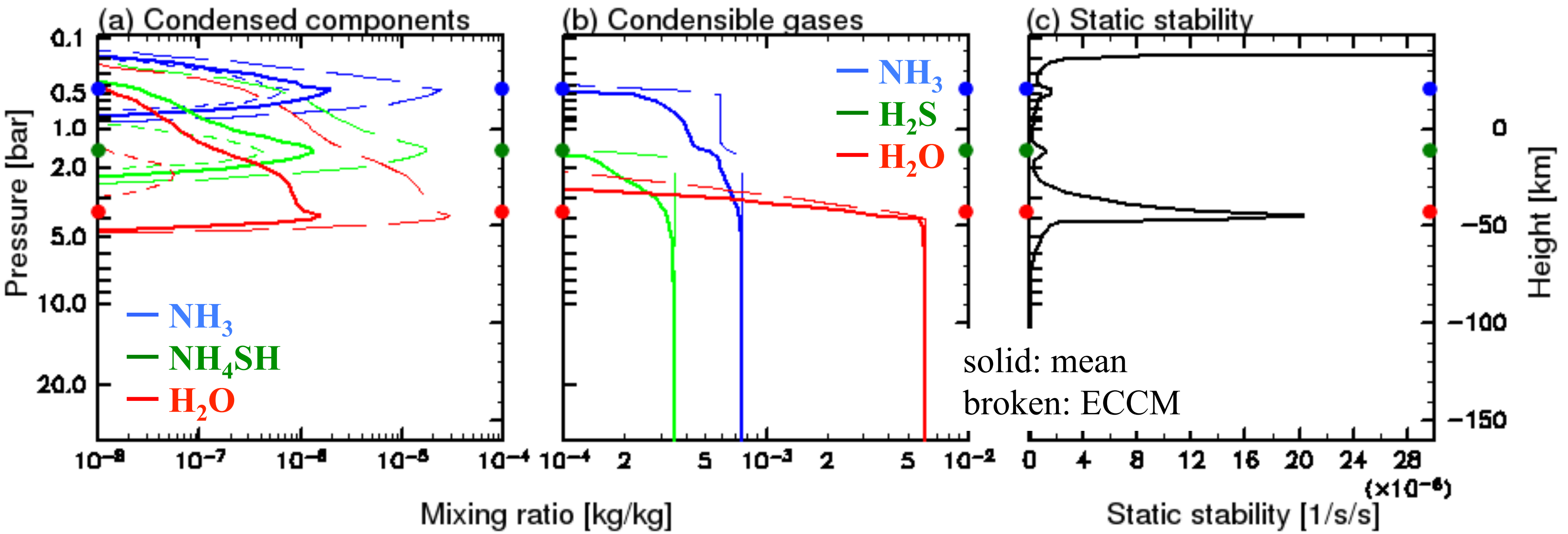
Mean structure: condensed components

- Horizontal mean profiles averaged over several cycles including active and quiet periods are shown.
- Considerable amounts of H_2O and NH_4SH cloud particles are observed above the NH_3 condensation.



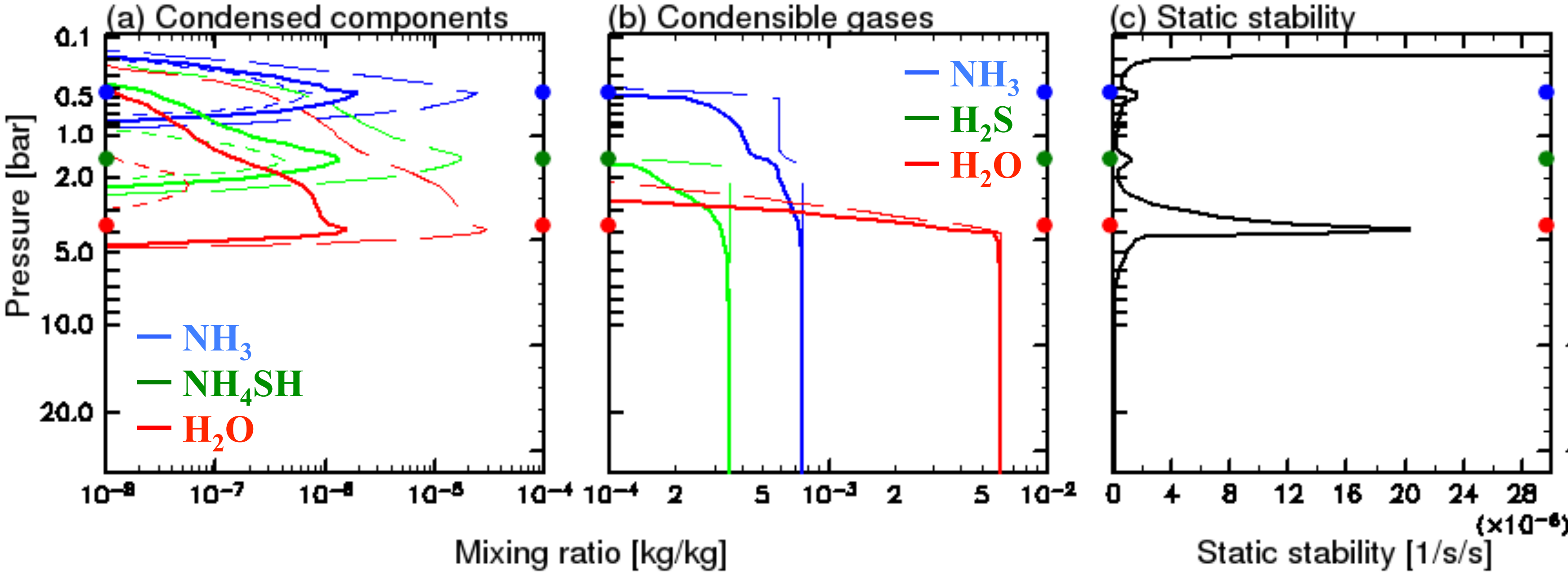
Mean structure: Condensible gases

- The mixing ratios of NH_3 and H_2S start to decrease with height not at their respective condensation levels but at the H_2O condensation level.
- The characteristics are not the same as that of the previous thermodynamical equilibrium calculations (ECCM).
  - Vertical mixing of dry and condensible during the active periods.



Mean structure: stability

- There is a distinct maximum of N^2 (the square of buoyancy frequency, N) at the H_2O LCL, which explains why the level acts as both a compositional and a dynamical boundary.
  - caused mainly by the change of mean molecular weight
- Weaker peaks are also present at the NH_3 and NH_4SH LCLs, which seem to act as dynamic and compositional boundaries to a certain extent during the quiet periods.



Concluding Remarks

- We perform a long-term numerical simulation with fixed thermal forcing

- The characteristics
  - Active cloud convection occurs intermittently.
  - The H_2O condensation level acts as a steady kinematic and compositional boundary.
  - The mean vertical distribution of clouds and condensible volatiles are distinctly different from those predicted by one-dimensional thermodynamical equilibrium calculations.
    - Considerable amounts of H_2O and NH_4SH cloud particles are observed above the NH_3 condensation.
    - The mixing ratios of all the volatiles start to decrease with height at H_2O condensation level.