Numerical Simulations of Jupiter's Moist Convection Layer: Structure and Dynamics in Statistically Steady States

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Introduction

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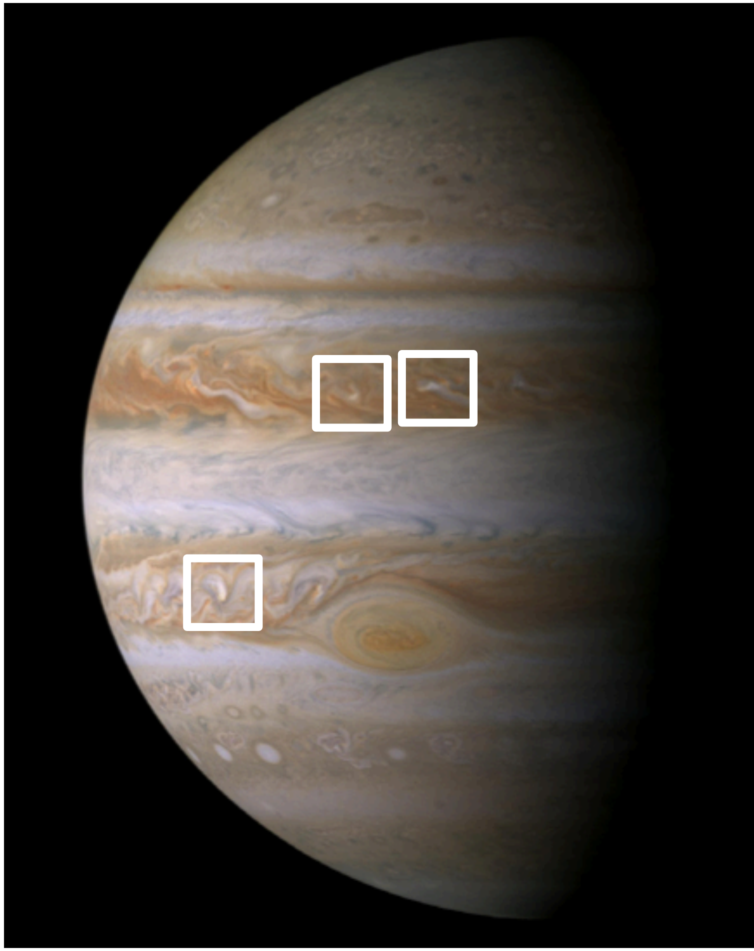
- The mean vertical structure of the cloud layer in Jupiter's atmosphere is thought to be maintained by the statistical contribution of a large number of clouds driven by internal and radiative heating/cooling over multiple cloud life cycles.
- However, the mean vertical structure and its relationship 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.



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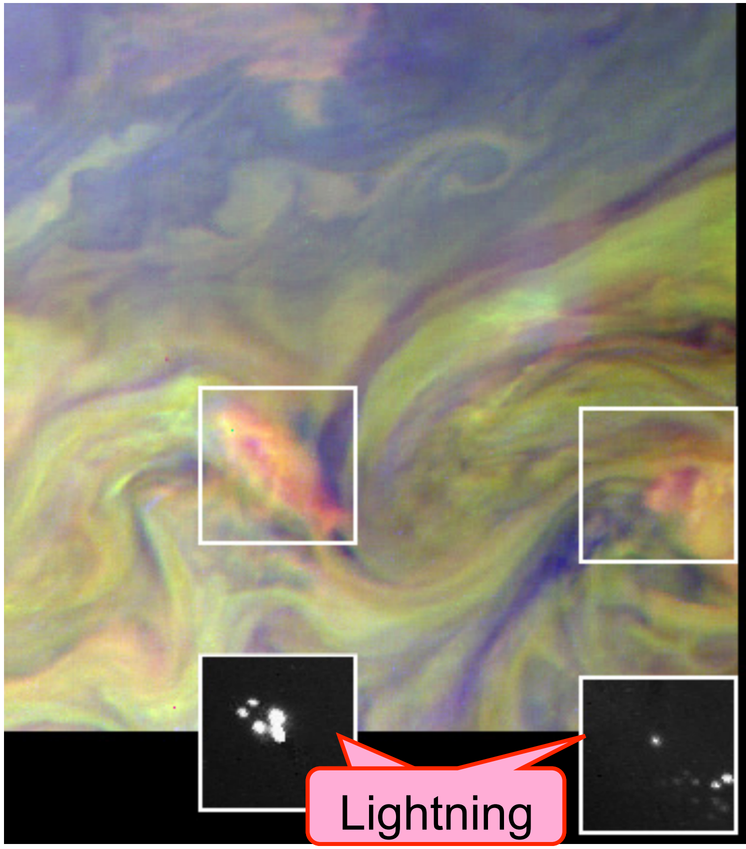


Fig. Convective clouds observed by Galileo (Vasavada and Showman, 2005)

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.

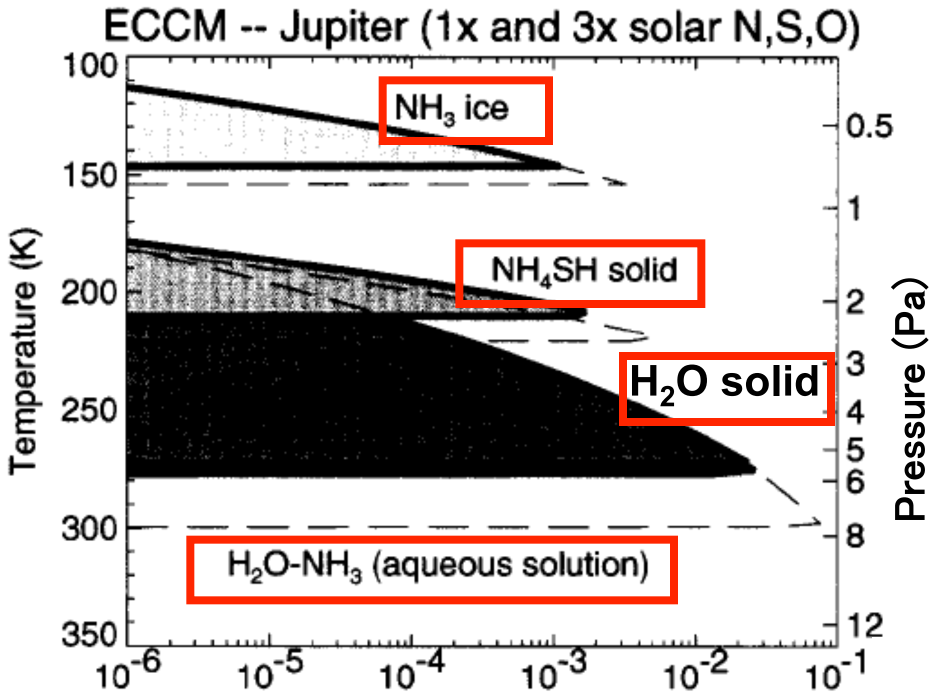
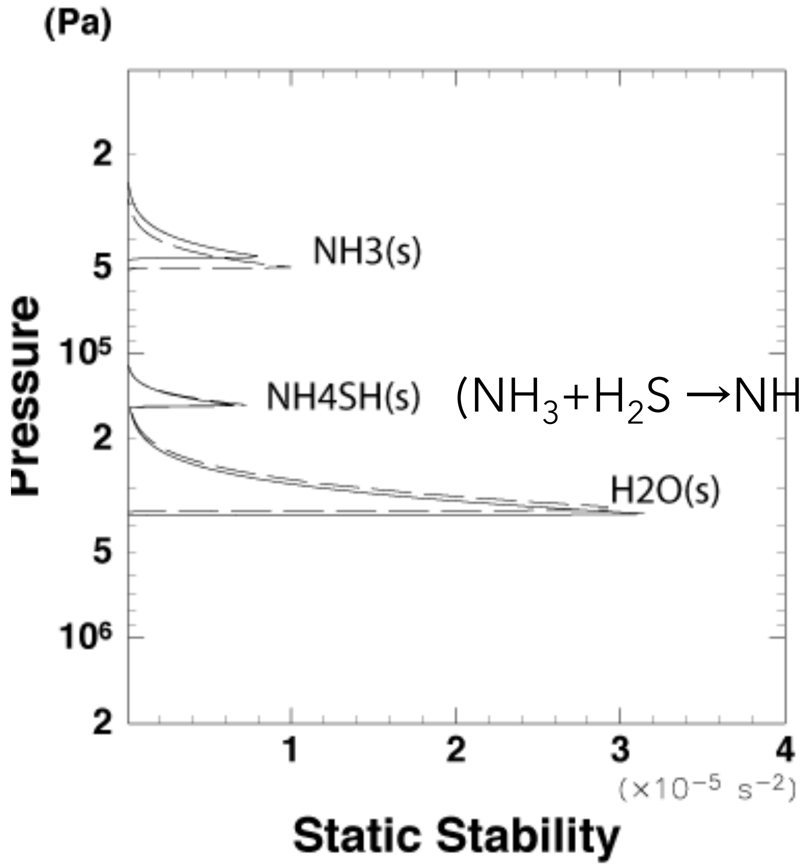


Fig. Vertical structure of Jupiter's cloud obtained by the equilibrium cloud condensation model (Atreya *et al*, 1999).

Three Cloud layers!

Introduction

- One of the important role of condensation is to form stable layers
- Molecular weight of each condensable gas (H_2O, NH_3, H_2S) is larger than that of major component (H_2 or He).
- If condensation occurs and the condensate is removed by precipitation, the mean molecular weight decreases and stable layer is formed.
  - Three-stable layers will exist in the moist convection layer.



($NH_3 + H_2S \rightarrow NH_4SH$)

Fig: Vertical profile of static stability estimated by using ECCM.

In our study

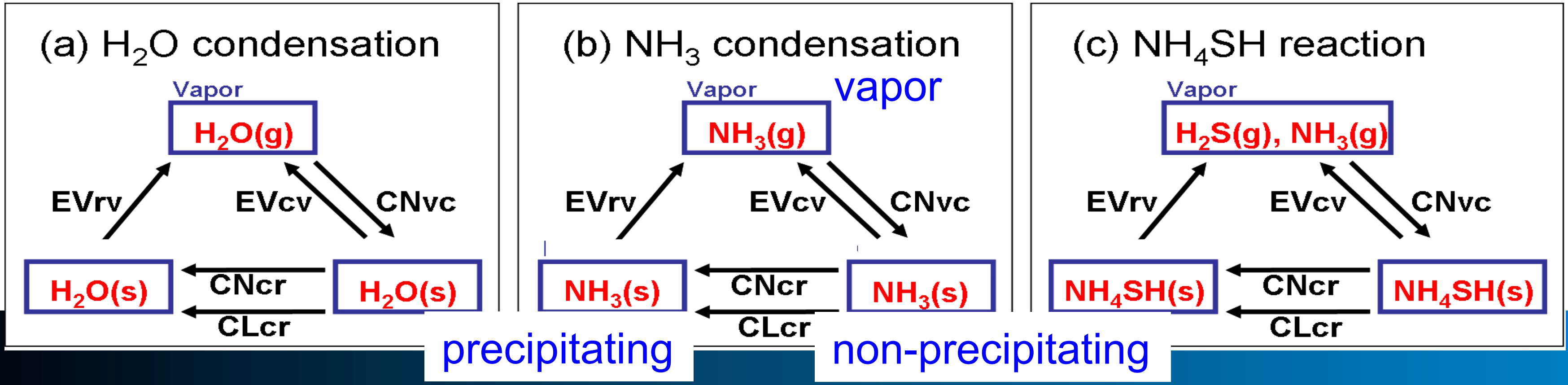
- We have been developing cloud resolving model (deepconv) that incorporates phase change and cloud microphysics.
- We investigate idealistic characteristics of convective motion and mean vertical structure of the moist convection layer that is established through a large number of life cycles of convective clouds.
  - Nakajima et al. (2000) [consider H_2O only]
  - Sugiyama et al. (2009, 2011, 2014) [consider H_2O, NH_3, H_2S]

- In this presentation,
  - We demonstrate the temporal variation of the characteristics in the moist convection layer.
  - The dependency on deep abundances of condensible gases are also demonstrated.

Model &
Setup of Exp.

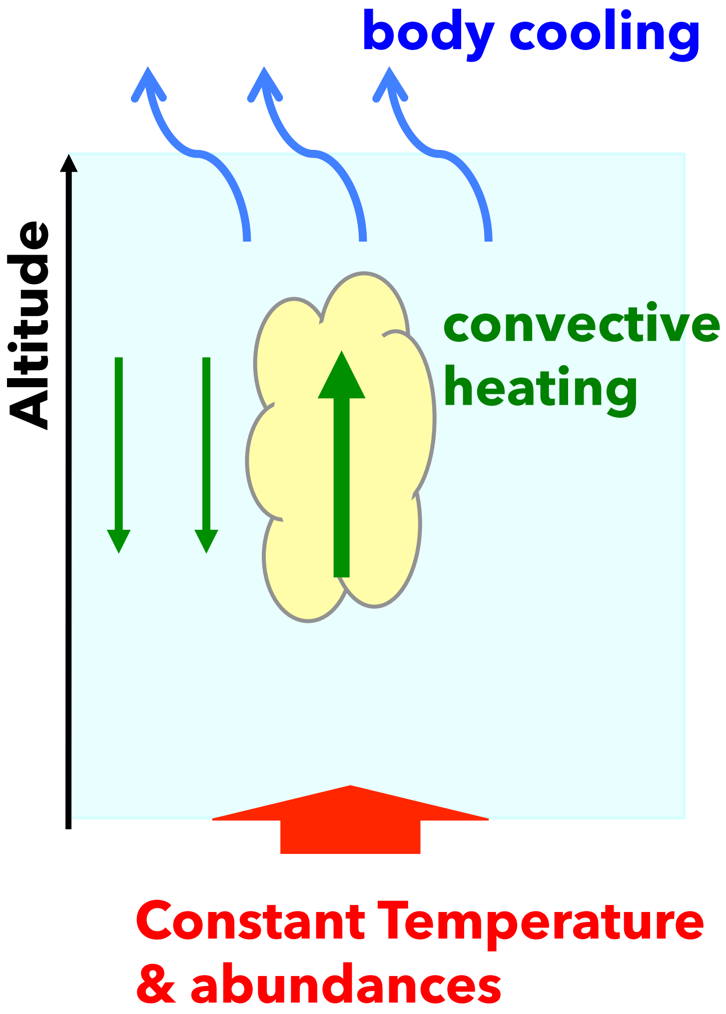
Numerical model

- The dynamical framework of our model is two-dimensional in the horizontal and vertical directions, and is 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 is very crudely represented.
  - Cloud microphysics process: The bulk parameterization scheme (vapor, non-precipitating and precipitating condensates) of Kessler (1969) that is well-used in Earth's atmospheric simulation is used.

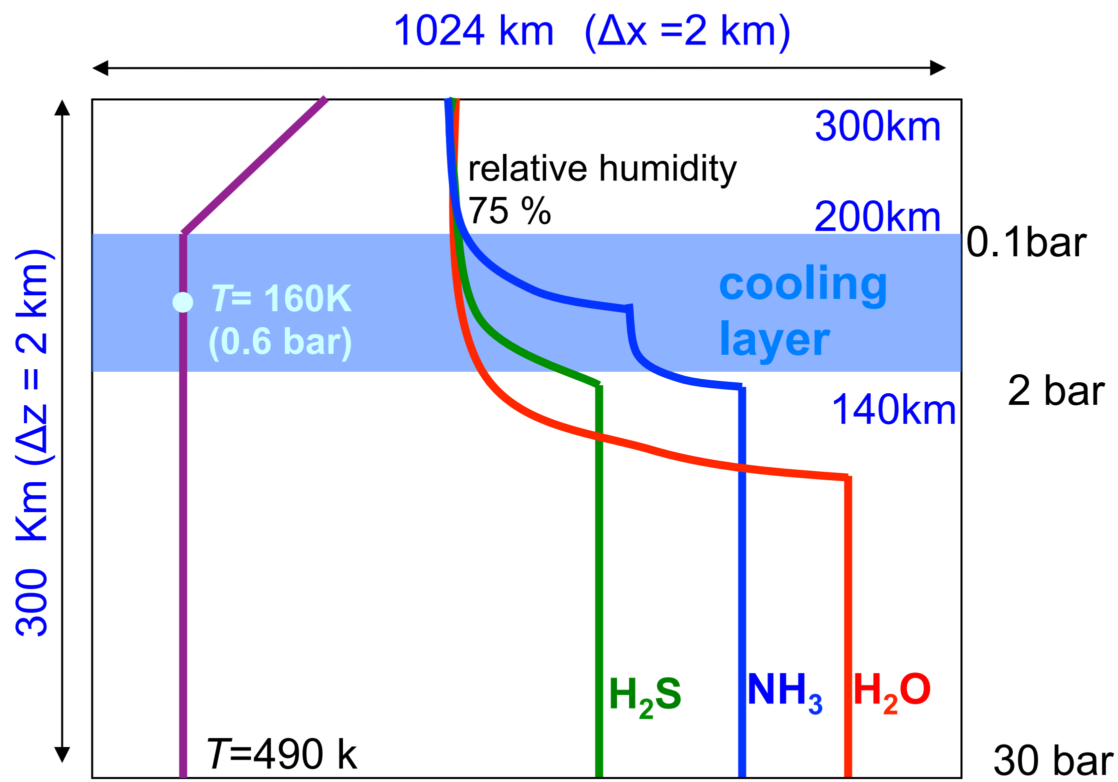


Set-up of the experiments

- The balance among the upwelling heat flux from the deep interior, the upward heat transport by moist convection, and net radiative cooling caused by solar and long-wave radiation is considered.
  - The effect of the heat supply from the deep interior is realized by keeping the values of the potential temperature and mixing ratios constant at the lower boundary.
  - The net radiative cooling is simply represented as horizontally and temporally uniform body cooling at the upper troposphere.



Set-up of the experiments



Initial potential temperature (θ)

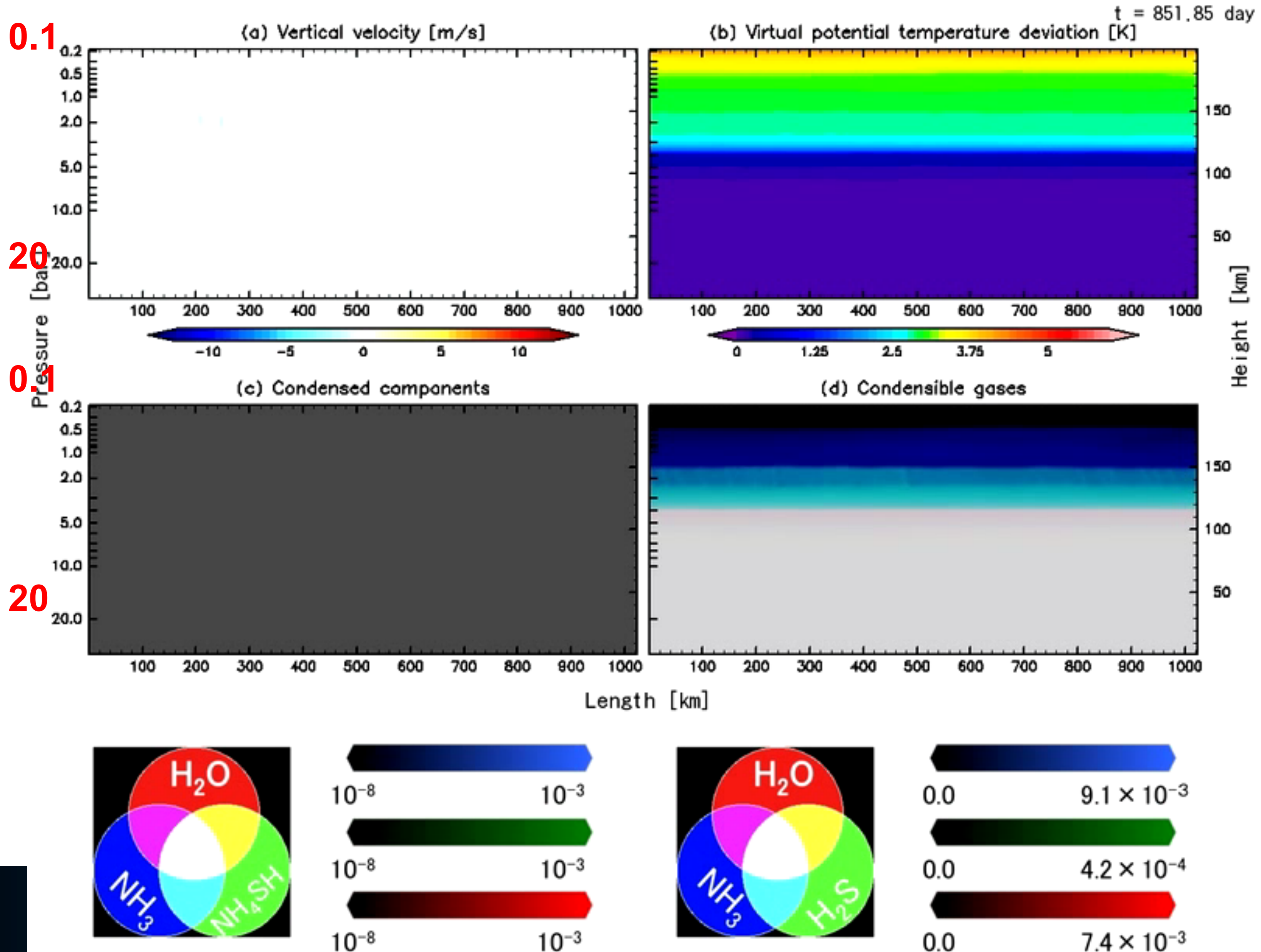
Initial mixing ratios (1, 3,10 times solar)

- Cooling rate (Q_{rad}):
  -0.01 K/day (typical value)
  -0.1 K/day
- deep abundances:
  1 x solar
  3 x solar
  10 x solar
  - The solar values are taken from Grevesse et al. (2007).
- Integral time
  - about 3 years

Results

We show the results of Control Exp. (CTRL) using Q_{rad} = -0.01 K/day and deep abundance is 1 x solar.

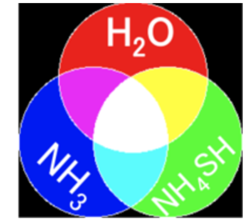
Animation

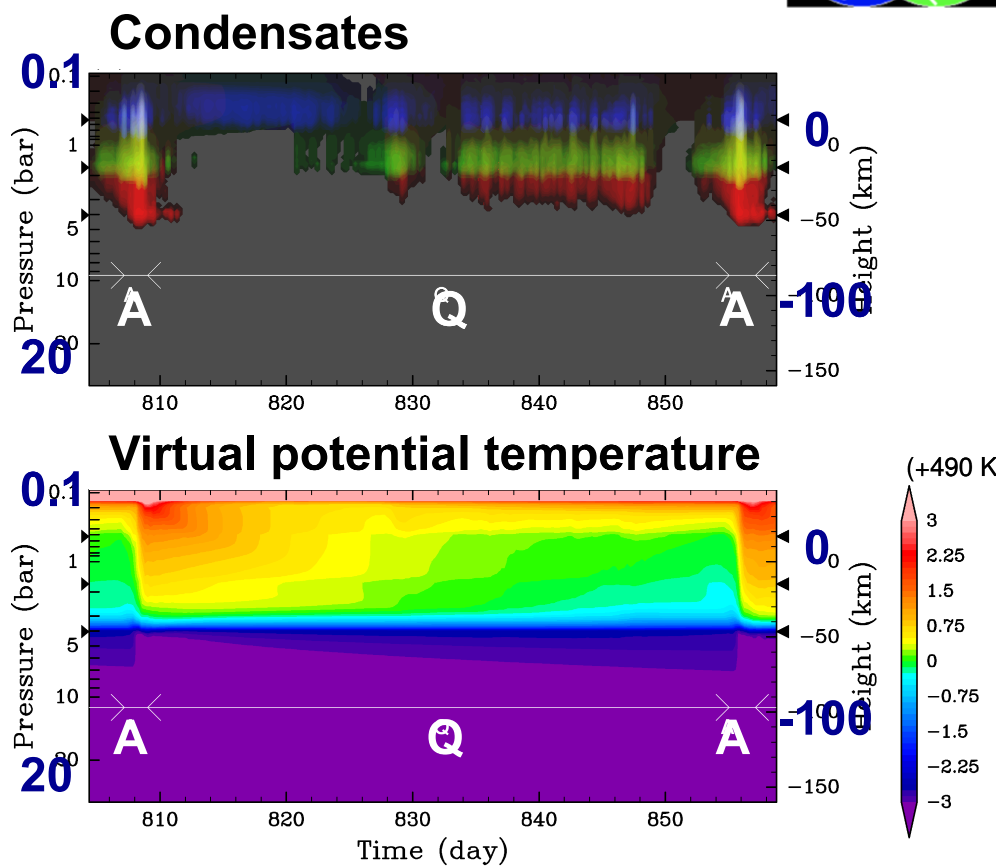


t = 851.85 day
(a) Vertical velocity [m/s]
(b) Virtual potential temperature deviation [K]
(c) Condensed components
(d) Condensible gases
0.1
20
Pressure [bar]
Height [km]
Length [km]
-10 -5 0 5 10
0 1.25 2.5 3.75 5
H_2O
NH_3
NH_4SH
H_2S
10^{-8} 10^{-3}
0.0 9.1×10^{-3}
0.0 4.2×10^{-4}
0.0 7.4×10^{-3}

Horizontal average

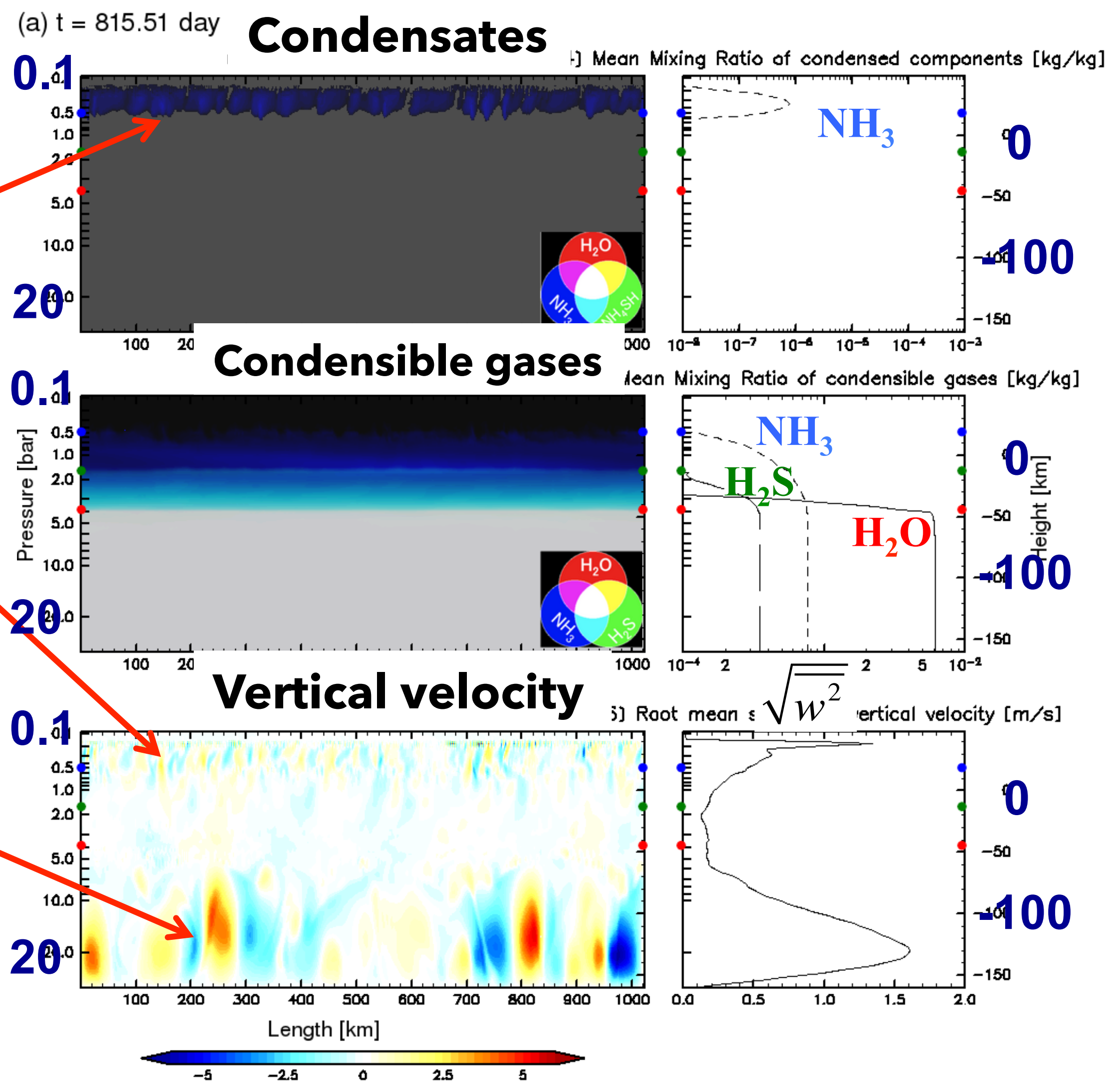
- The convective activity of the whole layer is not steady but quasi-periodic with a period of about 40 days.
  - We will refer the time when the active cloud convection occurs as `active period' (A) and the other as `quiet period' (Q).
- The value of virtual potential temperature rapidly increases during the active periods, and decreases steadily with time during the quiet period.





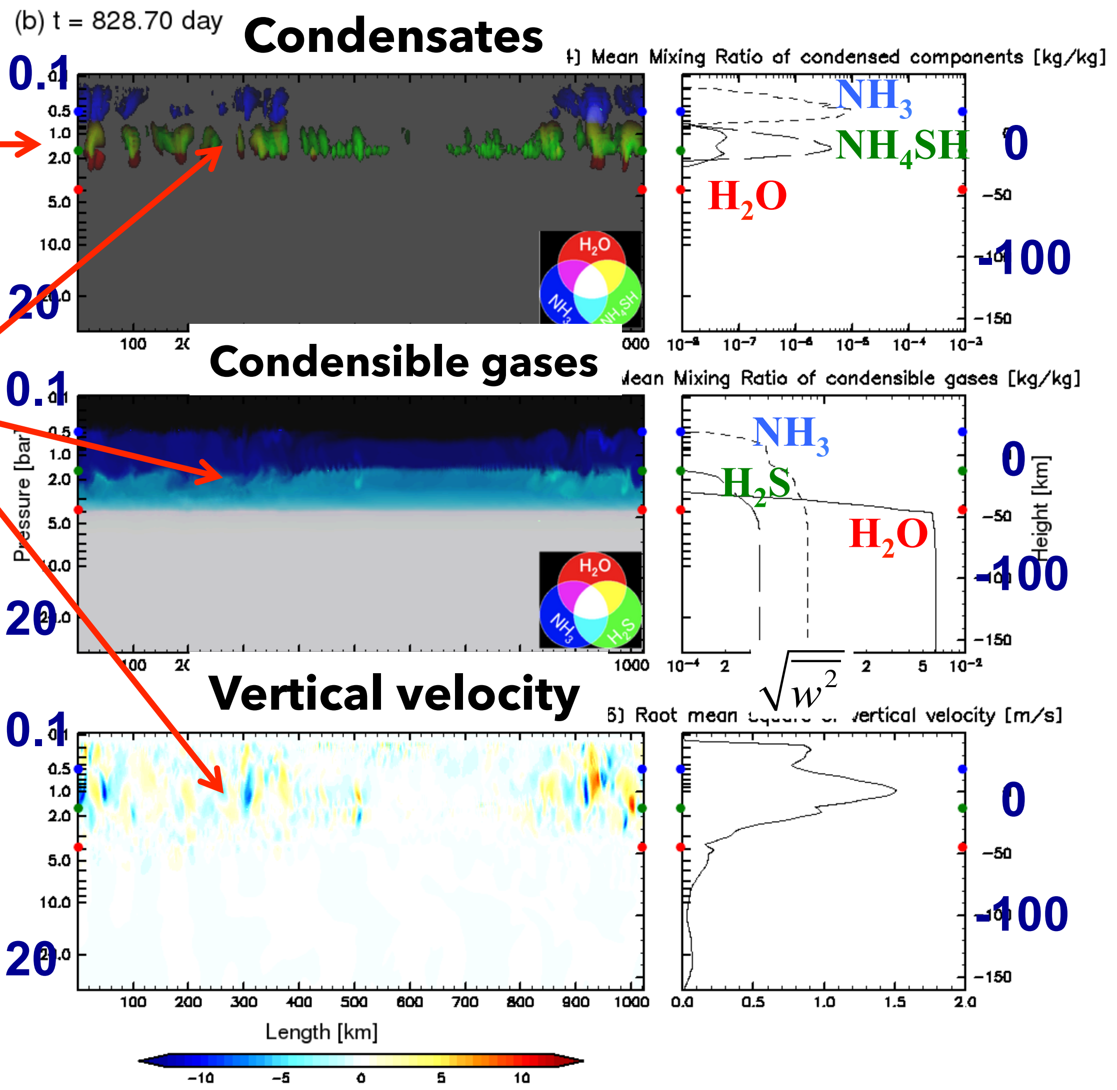
Development of clouds (1)

- At the beginning of quiet period, moist convection associated with NH_3 condensation occurs and the NH_3 clouds are distributed horizontally.
  - Vertical motion is weak ($w = \sim 5$ m/s)
- Note that the vertical motion in the sub-cloud layer is the remnant of convective motion driven during an active period.



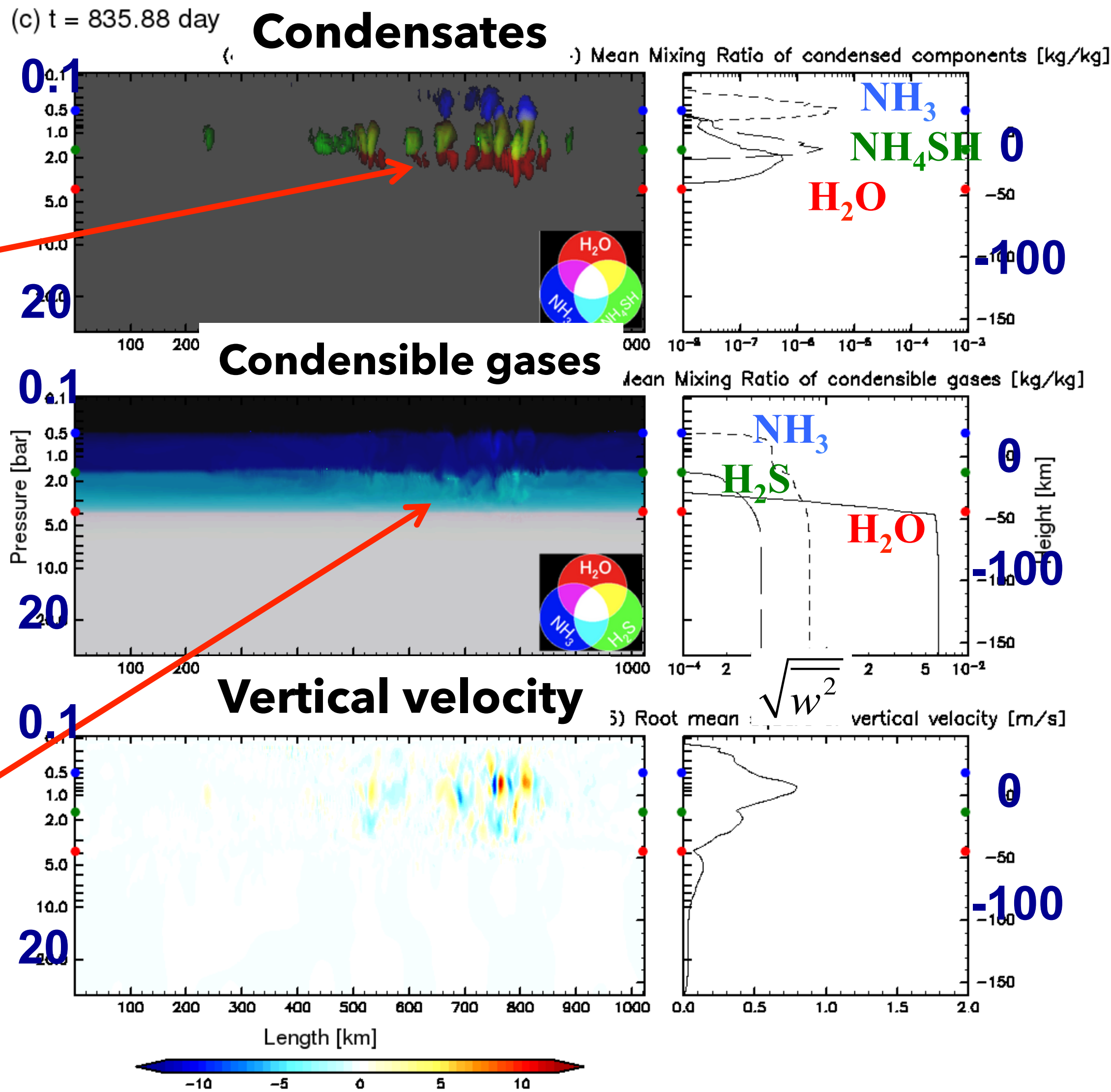
Development of clouds (2)

- As time progresses, NH_4SH clouds appear, followed by H_2O clouds.
- Mixing of different condensable gases and condensates across the NH_3 LCL or NH_4SH LCL is weak, but occurs occasionally due to the upward or downward penetration of convective plumes.
  - LCL is "lifting condensation level".



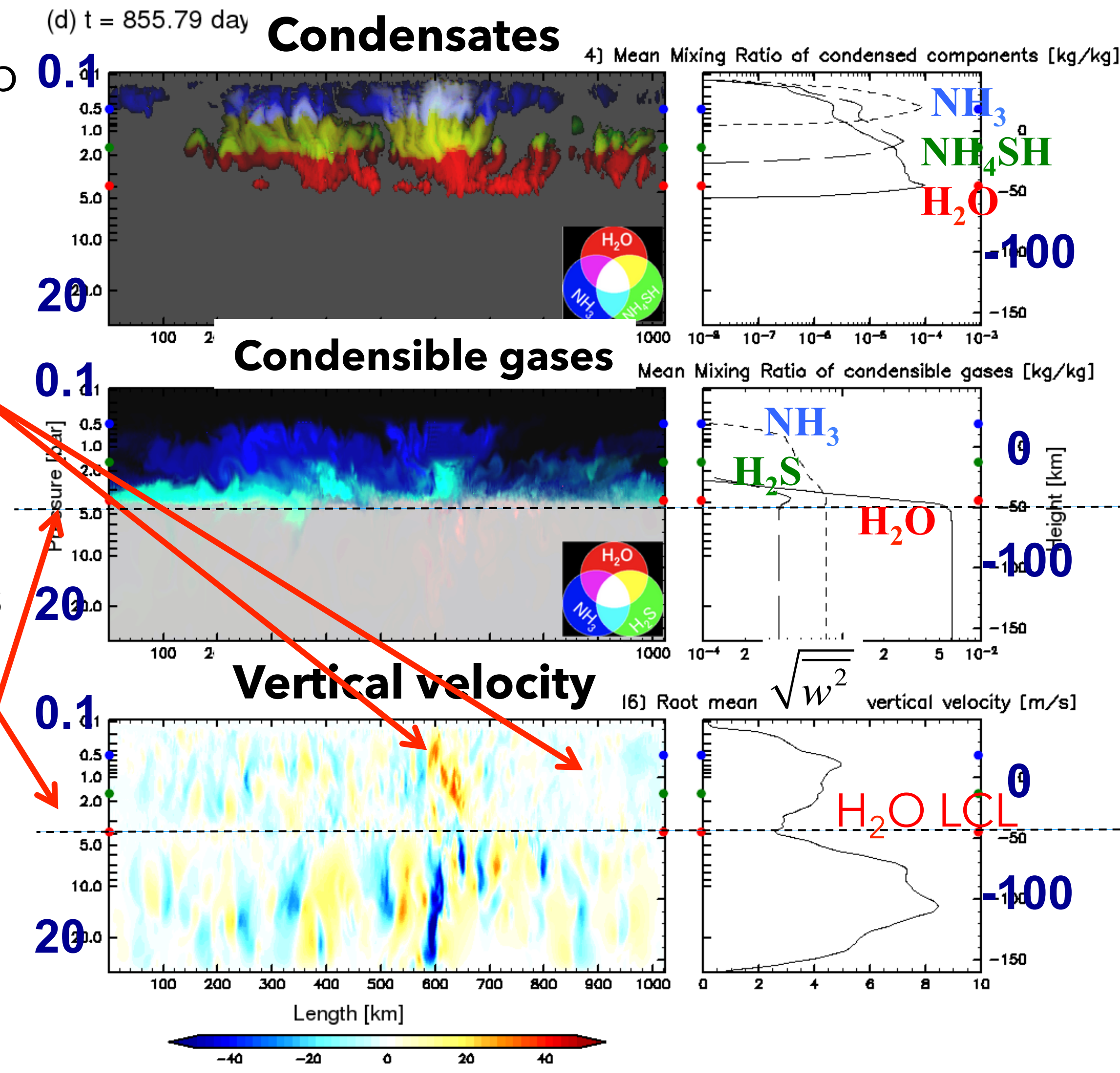
Development of clouds (3)

- Following the onset of NH_4SH clouds, stronger H_2O clouds begin to form and become localized.
  - The base of H_2O cloud is deeper than the previous time.
- Distribution of condensible gases is still almost horizontally uniform.
  - Mixing of different condensible gases across the NH_3 LCL or NH_4SH LCL is still weak.



Development of clouds (4)

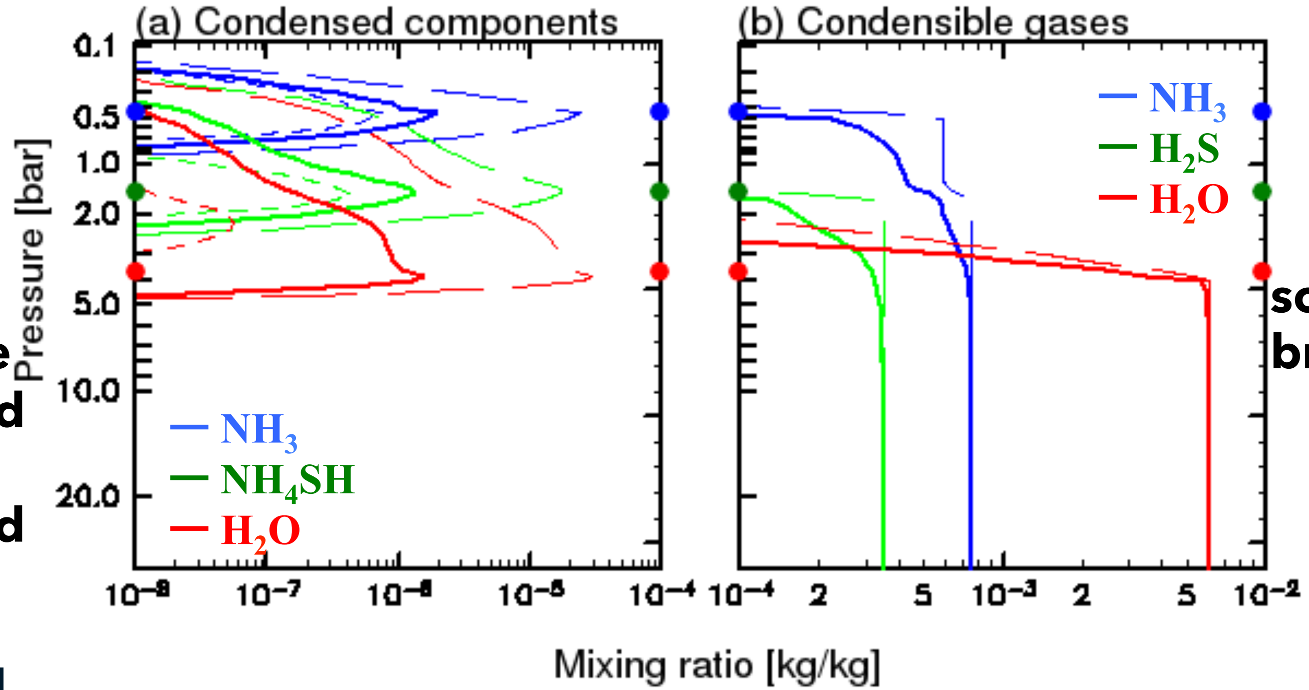
- H_2O active clouds develop from the H_2O LCL.
- The vertical motion in the moist convection layer is characterized by narrow, strong, cloudy updrafts and wide, weak, dry downdrafts.
- H_2O LCL continues to acts as a significant dynamical and compositional boundary.
  - Stable layer is exists
  - Updrafts and downdrafts penetrate the NH_3 and NH_4SH LCLs.



Time & horizontal average

- Considerable amounts of H_2O and NH_4SH cloud particles are observed above the NH_3 LCL.
- The mixing ratios of NH_3 and H_2S start to decrease with height not at their respective LCLs but at the H_2O LCL.
- These characteristics are not the same as that of ECCM.

solid: mean
broken: active period
dashed: quiet period



solid: mean
broken: ECCM

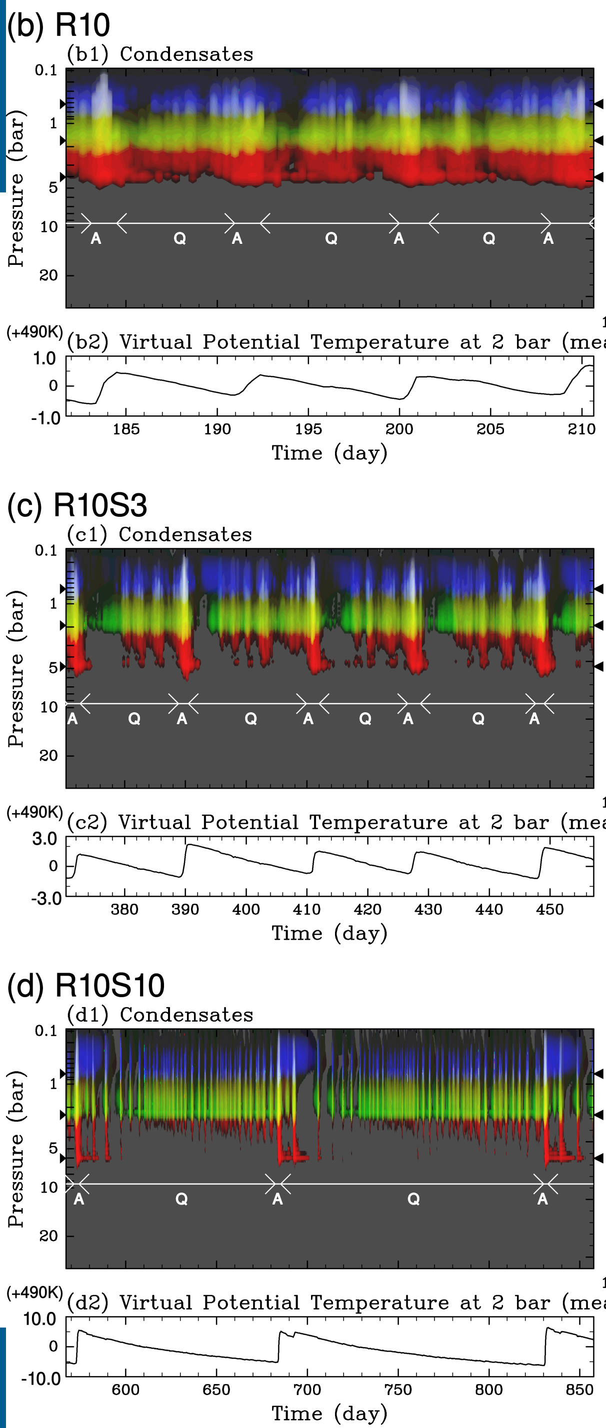
Dependency on deep abundance

The body cooling rate is set to be 10 times larger than that of CTRL in order to save the CPU time.

Dependency on deep abundances

- The results of the series of calculation are qualitatively similar to that of CTRL.
- The period of the quasi-periodic cycle is roughly proportional to the deep abundance of H_2O vapor.

	deep abundances (solar)	period (day)	ratio
R10	1	9	1
R10S3	3	19	2.1
R10S10	10	139	16

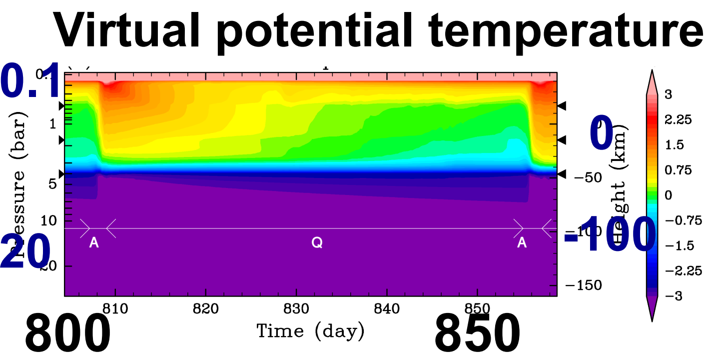


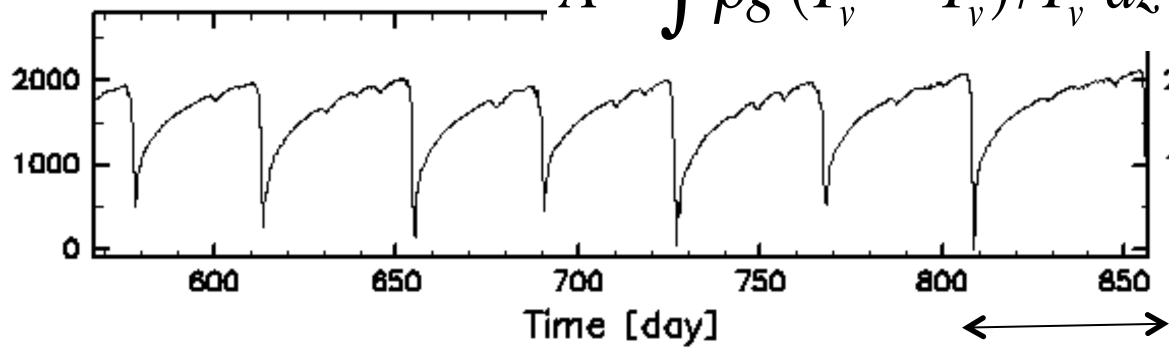
Discussion & Conclusion

Why intermittent?

- Active cloud development is terminated when the instability is completely exhausted.
  - An integral measure of convective instability (A) increase in the quiet periods and decrease rapidly in the active periods.
  - At the end of the active periods, A is almost z

$$A = \int \rho g \,(T_v^* - T_v)/T_v \, dz$$





- The trigger of active convections are H_2O condensate that falls down through the H_2O LCL.
  - The upward flow driven by H_2O re-evaporation carry moist air from below to the moist convection layer.
- The period of intermittency is roughly equal to the time obtained by dividing the mean temperature increase by the body cooling rate.

Summary

- Active cloud convection occurs intermittently.
  - The existence of vigorous cumulonimbus clouds is supported by several recent observational studies (Gierasch et al., 2000; Simon-Miller et al., 2000; Sromovsky and Fry, 2010).
- The H_2O condensation level acts as a steady kinematic and compositional boundary because of the strong stable layer associated with the H_2O condensation.
  - The present results do not reproduce the observation made by the Galileo probe that all condensable gases are depleted below the H_2O LCL (Wong et al., 2004).
  - Dry air parcels can rarely penetrate below the H_2O LCL, since the H_2O LCL acts as a strong dynamical and compositional boundary.
- The averaged vertical profiles of clouds and condensible gases are distinctly different from those predicted by ECCM.
  - By considering the vertical mixing due to convection, the small NH_3 abundance derived from analysis of radio observation (Pater et al., 2001, Gibson et al., 2005) can be explained.
- The period of the quasi-periodic cycle is roughly proportional to the deep abundance of H_2O gas.