P31D-2854: *Longevity of Compositionally Stratified Layers in Ice Giants*

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ABSTRACT

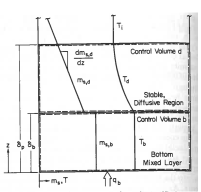
In the hydrogen-rich atmospheres of gas giants, a decrease with radius in the mixing ratio of a heavy species (e.g. He, CH_4, H_2O) has the potential to produce a density stratification that is convectively stable if the heavy species is sufficiently abundant. Formation of stable layers in the interiors of these planets has important implications for their internal structure, chemical mixing, dynamics, and thermal evolution, since vertical transport of heat and constituents in such layers is greatly reduced in comparison to that in convecting layers. Various processes have been suggested for creating compositionally stratified layers. In the interiors of Jupiter and Saturn, these include phase separation of He from metallic hydrogen and dissolution of dense core material into the envelope consisting of metallic-H envelope. Condensation of methane and water has been proposed as a mechanism for producing stable zones in the atmospheres of Saturn and the ice giants. However, if a stably stratified layer is formed adjacent to an active region of convection, it may be susceptible to progressive erosion as the convection intrudes and entrains fluid into the unstable envelope. We discuss the principal factors that control the rate of entrainment and associated erosion and present a specific example concerning the longevity of stable layers formed by condensation of methane and water in Uranus and Neptune. We also consider whether the temporal variability of such layers may engender episodic behavior in the release of the internal heat of these planets. This research is supported by a grant from the NASA Solar System Workings Program.

Mechanisms for creating compositionally stratified layers

Mechanism	Planets	Refeerences
Condensation (Water or Methane)	Gas and Ice Giants	Guillot 1995 Friedson & Gonzales 2017 Leconte et al. 2017 Li & Ingersoll 2015
Helium Separation	Gas Giants	Vazan et al. 2016 Püstow et al. 2016
Core Dissolution into Metallic-H Envelope	Gas Giants	Wilson & Millitzer 2012

Various mechanisms have been proposed to create compositionally stratified stable layers deep in the gas and ice giants, as shown above. They all produce a mean molecular weight gradient that stabilizes an otherwise thermally unstable profile against convection. Here we focus on the condensation mechanism and its relevance to the ice giant's structure, mixing, and thermal evolution (Friedson & Gonzales 2017, Leconte et al. 2017). The molecular weight gradient in this case is caused by the decrease in condensable mixing ratio due to saturation and precipitation. In particular, we focus on the question of potential **UNSTEADINESS** in the interaction between the stablized layer and adjacent convective layer, which has received relatively little attention.

A



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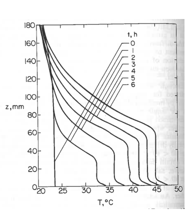

Convective Entrainment of Salt-Stratified Layer in the Laboratory

The figures to the left show the results of an experiment to measure entrainment rates determined from mixed layer growth in a salt-stratified medium heated from below. **(A)** Schematic of the system, showing the mixed layer overlain by a stable, salt-stratified, diffusive region. **(B)** Vertical temperature profiles in the system versus time. The regions of quasi-uniform temperature correspond to the mixed layer, which gradually grows and entrains the stably stratified layer as it expands upward. Figures taken from Bergman et al. 1986.

A similar process may occur In the ice giants. Instead of salt, the stratification is provided by water (or methane) condensation, and the mixed layer lies above the stable water condensation zone and erodes it from above as it expands downward. The mixed layer is driven by convective cooling in the outer envelope, itself driven by the planet's inexorable cooling to space.

References

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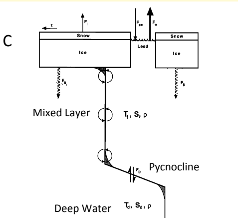
An Example from Nature: Overturning of the Halocline in the Southern Ocean

A stable pycnocline generally exists in the high-latitude Southern Ocean between salty warm Antarctic bottom water and relatively cold and fresh surficial water. The pycnocline is stable due to the salinity gradient (halocline) separating the deep water and mixed layer. A schematic of the system is shown in **Fig. C**. The pycnocline is the region where the density sharply decreases; the mixed layer overlies this region.

C



From Martinson et al. 1990

In some years, salt rejection from freezing ice increases the salinity of the mixed layer to the point where the pycnocline is significantly diminished. In the area of the Weddell Sea, the initially thin pycnocline can sometimes be eroded entirely, leading to overturning, a large heat flux, and production of a large polynya (ice-free area within the polar ice sheet). **Fig. D** shows the return of the Weddell Sea polynya in 2017, which was last seen in the late 1970s.

D

Credit: Jan Lieser, ACE CRC, Australia

Entrainment of the Water Condensation Zone (WCZ) in the Ice Giants: Our Model

In many respects, the density profile in the outer layers of a cooling ice giant resembles that of the Southern Ocean. The water condensation zone (WCZ) provides a pycnocline; the overlying convecting envelope corresponds to the cold oceanic mixed layer; and the water-rich atmosphere below the base of the WCZ corresponds to the deep, salty Antarctic bottom water. As the planet cools, convection causes the mixed layer to entrain and expand downward into the stable WCZ, eroding it from above. (This is like the laboratory experiment shown in Figs. A and B turned upside down). Extensive cooling may erode the WCZ pycnocline entirely, leading to catastrophic overturning and rewetting of the mixed layer, or alternatively leave a thin but stable residual boundary layer separating relatively cold, dry mixed layer air from heavy, water-rich abyssal gas. What actually occurs has important consequences for our understanding of the degree of compositional mixing in the ice giants, and for their thermal history and internal structure.

We explore the entrainment of the WCZ in ice giants using a model inspired by studies of the Southern Ocean (Martinson et al. 1990). Water takes on the role of salinity. We assume:

1) Water is maintained in saturation at all levels and times
2) The system initially resides on a single pseudoadiabat associated with the time the WCZ is first effective as an insulator. As time progresses, the mixed layer and the WCZ lie on different pseudoadiabats, separated by temperature and humidity jumps at the base of the mixed layer. Below the WCZ, the abyssal atmosphere is steady and follows a dry adiabat.
3) The Nusselt number of diffusive convection in the WCZ is of order unity.

Because it is constant on a pseudoadiabat, we use moist static energy (MSE) [h, where $dh = C_p dT + g\ dz\ + L\ dq/(1-q)$], as the primary thermodynamic variable. We solve for the evolution of the MSE in the mixed layer as follows:

$$\frac{d}{dt}(\mathbf{MSE}) = \mathbf{Nu} \cdot \mathbf{RF\text{-}CF + EF}$$

$$\frac{dP_e}{dt} = -\chi \frac{g}{C_p T}(\mathbf{Nu} \cdot \mathbf{RF\text{-}CF})$$

Details: RF=radiative diffusion at base of mixed layer, CF= convective flux at top of mixed layer, and EF=entrainment flux at base of the mixed layer. Nu = Nusselt number in WCZ. P_e is the pressure at the entrainment level, which increases when CF > Nu RF. The factor χ depends on the pressure and temperature dependence of the saturation specific humidity and on the MSE difference between the mixed layer and abyssal layer, and decreases as this difference increases during the entrainment process. RF is calculated using the Rosseland opacity parameterization of Valencia et al. 2013; CF is computed from the pseudoadiabat equivalent potential temperature using the atmosphere grid of Fortney et al. 2011.

Example: Effect of the WCZ on the Cooling History of Uranus

We have just begun applying the model to explore the potential effect of the WCZ/mixed-layer interaction on the cooling histories and structures of the ice giants. We present PRELIMINARY results for Uranus. An obstacle to obtaining more definitive results is that we do not yet have a model for what happens when the WCZ becomes completely eroded: Does the system then undergo a major overturn with substantial mixing between the outer mixed layer and abyssal layer, or does it settle into two quasi-steady layers separated by a shallow diffusive interface -- an upper cold, dry layer overlying a warm, wet deep layer? Without the answer we cannot model the thermal evolution from "end to end", but we can explore some of the consequences of certain assumptions.

E

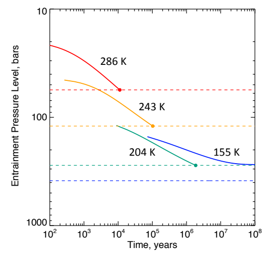


Fig. E shows the evolution of the entrainment pressure level P_e (base of the mixed layer) for four different assumptions for the initial pseudoadiabat, labelled by the temperature they produce at the 10-bar level. The water mass mixing ratio below the WCZ is assumed to be 0.25 (~50 x solar O). The dashed lines show the base of the WCZ for each case. The cooler the pseudoadiabat, the deeper are the initial entrainment level and base of the WCZ. As time progresses, the entrainment level moves down and, for the three warmer cases, reaches the base of the WCZ, indicating its complete erosion, within a time between ~10^4 to ~10^6 years. The filled circles indicate the point of complete erosion. In contrast, the WCZ for the coolest case (blue) persists for at least 10^8 years.

F

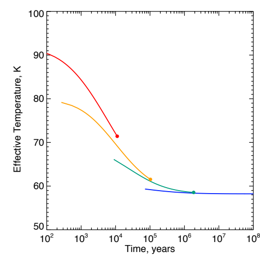
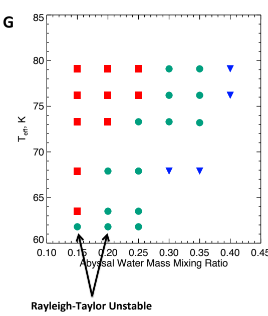


Fig. F shows the evolution of the planetary effective temperature corresponding to the four cases of initial pseudoadiabat shown in Fig. E. The connection between 10-bar temperatures and effective temperatures is made using the atmosphere grid of Fortney et al. 2011. The filled circles again show the point of complete erosion of the WCZ. Effective temperatures decrease rapidly (over intervals less than 10^6 years for the warmer cases) during the period prior to WCZ erosion. This is because the WCZ acts as an insulator that allows the mixed layer to decouple from the deep atmosphere, effectively lowering its heat capacity and speeding the cooling rate of the outer layer. *Unfortunately, we do not yet know what happens at the end of these trajectories*. The atmosphere could either overturn, resetting the clock and leading to a highly episodic cooling rate over geologic time, or settle into a 2-layer system that slowly cools "in place" over geologic time (or a combination of these could ensue at different times).

G



The abundances of water in the envelopes of Uranus and Neptune are unknown. **Fig. G** displays a grid of results illustrating the model's behavior for different assumed abyssal water abundances and different assumed initial pseudoadiabats, labeled here by the value of the initial effective temperature they engender. The RED SQUARES represent the cases where the WCZ has completely eroded before Uranus' T_{eff} = 59.1 ± 0.3 K is reached. For the GREEN CIRCLES, the atmosphere cools below this T_{eff} before the WCZ is completely eroded. For the BLUE TRIANGLES, the atmosphere cools below this T_{eff} and the WCZ persists beyond the model integration time (10^8 years). *If overturning ensues once the WCZ is completely eroded, then the red and green symbols represent states with cyclic behavior in the effective temperature, and in particular, the green circles mark cycles that would include Uranus' and Neptune's observed effective temperatures*. Therefore, the currently observed effective temperatures of the ice giants may arise from their phasing within this cyclic behavior; the disparity in their intrinsic luminosities may then simply reflect different phasing within similar cycles. In addition, the two dryer green states indicated evolve to Rayleigh-Taylor unstable configurations when the WCZ disappears, meaning they must overturn.

Takeaways

1) Potential unsteadiness of compositionally stratified layers must always be considered
2) The WCZs in the ice giants, although convectively stable for sufficiently water-rich compositions, were likely susceptible to complete erosion by entrainment into the overlying convective envelope during the planet's cooling history
3) Cooling times for the convective envelope above the WCZ are generally short, less than ~10^7 years, meaning the planet's effective temperature can decrease dramatically on this time scale
4) Overturning accompanying complete erosion of the WCZ could engender episodes of cyclic behavior in the effective temperature, superimposed on the slow secular cooling of the planet
5) Uranus and/or Neptune may currently be trapped in a cooling/overturning cycle. If so, the disparity in their intrinsic luminosities may reflect a difference in where they currently reside within their individual cycles.