Response to the comments of Dr. Carpenter.

- Dear Dr. Carpenter,
- Thanks a lot for your time and effort in reviewing our paper. We are glad that you have provided us an alternative view of the diffusive convection. Below are our responses to your comments.

In this paper the authors have applied the classical linear stability results for a double diffusive stratification of the diffusive type to the deep thermohaline staircase of the Canada Basin, Arctic Ocean. There are a number of arguments made in the application of the theory to the observations that I have found difficult to follow. I list some of the difficulties that I have had below.

(1) The last sentence of the paragraph around line 20 on page 1350. I don't understand what assumption is being referred to here. As far as I understand the authors have used the linear stability theory developed for a layer of height L, with constant gradients of T and S inside (i.e., linear T and S profiles) that is bounded by rigid free-slip surfaces above and below. This has been applied in this section to the interfaces themselves, i.e., neglecting the fact that there are mixed layers on either side and assuming rigid boundaries. According to the theory this system predicts that an (oscillating) instability will occur when R_rho<1.15 (approximately). If this very idealized setup is assumed to apply to the interface region only then there is no instability because we have all interfaces with R_rho>2. Is this a correct interpretation?

- We are sorry that the presentation here is not clear. The assumption is that the Rayleigh number based on the boundary layer is of the order of the critical value, Rac. In the single layer thermal convection, this assumption was first proposed by Howard (1964), and was applied in many other studies (see references in Siggia (1994)). In addition, this assumption was confirmed to be marginally correct in the laboratory experiments (Castaing et al., 1989).
- You are correct. The predictions of linear stability (Eq.(5)) is to describe the new formation of convecting layer in diffusive convection. Analogous to the description of single-layer thermal convection, a convecting layer should include a mixed layer and approximately half of its top interface and half of its bottom interface so that the convection rolls in each layer can be treated as a whole system.
- The argument here arises from different definitions of the boundary layer.
  - To the diffusive convection, the boundary layer model was proposed by Linden & Shirtcliffe (1978). In this model, the boundary layer, δ, is defined as $\delta=(h_T-h_S)/2$, where h_T and h_S are the thicknesses of interface based on temperature and salinity. This model has been further employed in many studies, e.g. Newell (1984), Worster (2004), and your works (Carpenter

2012JPO, Carpenter 2012JFM). We agree that results from these studies enriched our understandings on the instability of diffusive convection.

- ◆ On the other hand, in the thermal convection (single layer convection), the thermal boundary layer is defined as the region of high temperature gradient. This definition was used in many thermal convection studies, e.g. Lui, and Xia (1998), Puits et al. (2007). Similar to thermal convection, the thermal boundary layer of the convecting layer in diffusive convection is also defined as the region of high temperature gradient, so does the salinity boundary layer, which corresponds to the interface. To each convecting layer, the thermal boundary layer is approximated as the half interface thickness, $\delta=h_T/2$. This definition is used in some studies of in situ observation, e.g. Padman & Dillon (1989), Sanchez & Roget (2007), and the numerical simulation in astrophysics, e.g. Zaussinger F., & Spruit (2013). By this definition, some results of single layer convection can be extended to explore the convecting layer in diffusive convection. In the present manuscript, we use this definition. The interface is taken as the boundary layer of the convecting layer. In this case, the convecting layer cannot exist without the mixed layer. We are sorry that we did not make a distinction between the thermal boundary layer and the salinity one due to technical reasons. For these in situ ocean data measured by CTD, the salinity is calculated from the measured temperature and conductivity of sea water. Therefore, the salinity profile is affected by the temperature profile.

(2) If I have understood correctly, the authors next seem to apply the same linear stability model to the boundary layer. They make a choice for the salinity Rayleigh number that is based on the mean background gradient averaged over many of the staircase steps, and cite the work of Turner (1968). I don’t see how this is justified since the boundary layer of an interface within a much larger staircase certainly can not know what the large-scale mean gradient is. In the Turner experiments he studied the formation of a staircase into a uniform salinity gradient by heating from below – in this case the argument of using the background gradient is valid because that is the gradient in the boundary layer. Can the authors please comment on this interpretation of their analysis?

- ➢ In the ocean, the background salinity gradient is obtained by the linear fitting to the salinity profiles in a limited depth range, where the diffusive convection staircases are included, as shown in Fig. 1 below. When the onset of a new convecting layer happens, it is assumed that the background salinity gradient remains unchanged because the salt diffuses much more slowly than heat. In this case, the prediction of linear stability can be used to describe the onset of convection, similar to the laboratory experiment in Turner (1968).

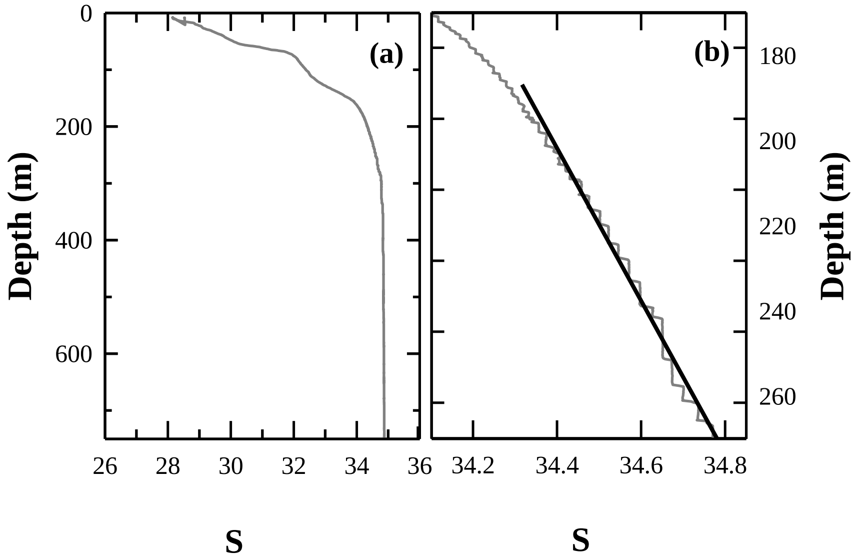

Fig.1 A typical salinity profile in the Canada Basin. The salinity profile where the DC staircases are included is linear fitted to get the background salinity profile.

(3) In general, as far as I can see, the linear stability theory that has been applied is for a different type of instability than is present in a double-diffusive staircase, i.e., at an interface. The theory used is for the classical oscillating instability of smooth (linear) gradients of T and S, in which the density ratio 1 < R_rho < 1.15, or if R_rho<1 then a salinity stabilized convection. Carpenter et al. 2012 (see references in the discussion paper) have showed that the instability that is present at a diffusive interface (without rotation) is in agreement with the Linden & Shirtcliffe (1978) view, namely, that the T interface grows much faster than S due to the larger diffusivity, and produces unstable thermal boundary layers. The instability is a direct convective mode of the diffusive boundary layers, not of the oscillating diffusive convection type. The analysis shows that the boundary layer length scale can not be taken as the interface thickness because the salinity stratification is overwhelmingly stable (otherwise you would not have a staircase, it would all be completely mixed), and can not be considered as the mean background gradient. On top of all of this is the fact that the instability at a diffusive interface is due to the thickening T interface (relative to S), and this changing background state violates the assumptions of a stability analysis.

- We agree with your description of the diffusive boundary layer. However, if the assumption that the background salinity gradient remains unchanged at the onset of convecting layer is applicable, the predictions of linear stability (Eq. (5)) might be used to describe the formation of new convecting layer. Our colleague, Dr Cen Xian-rong, has taken a 2D DNS simulation of diffusive convection in a linear salt-stratified tank, which is similar to the experimental setup of Turner (1968) as well as the numerical simulation of Molemaker (1997). We focus on the formation of the second convecting layer, the corresponding density ratio (Rρ) as a function of time (t) is shown in Fig. 2 below. It can be seen that Rρ has a minimal value at the threshold time, t_0. When time approaches t_0, Rρ is in the valid range of predictions of linear stability (Eq. (5)).

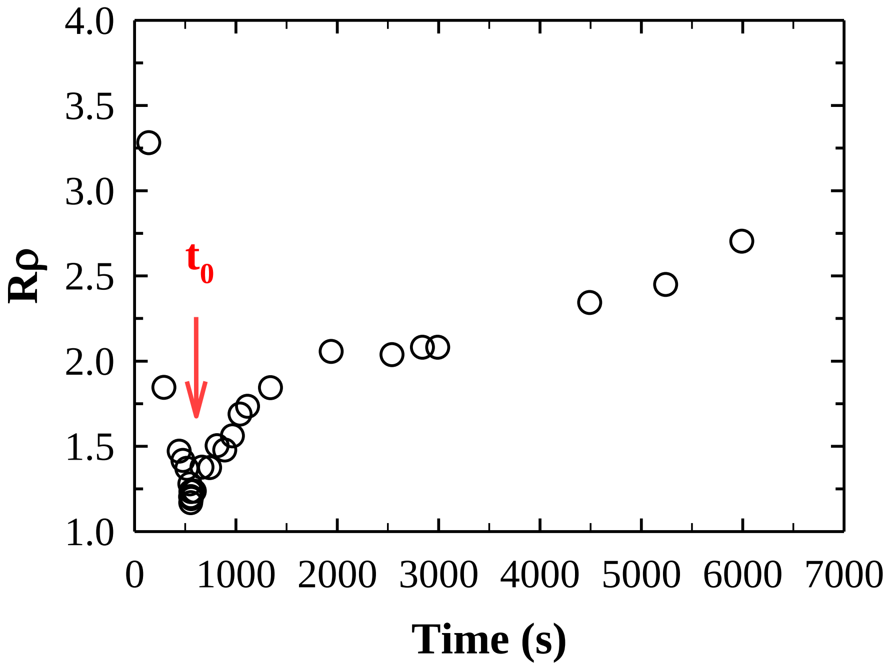

Fig. 2, The density ratio (Rρ) as a function of time (t) of the formation of the second convecting layer. Here we just give a brief introduction of our numerical experiment. We consider a rectangular box (aspect ratio A = 1) with height of 0.1 m; an initially isothermal motionless solution (Pr = 7, $\tau = 0.01$) is continuously heated from below; the prescribed buoyancy flux is $q_0 = 1.02\times10^{-6}$ m^2s^{-3}, and the initial buoyancy frequency is $N = 1.58$ s^{-1}; the solution is assumed incompressible and the Boussinesq approximation is used in the simulation. Rρ before the layer formation is calculated from the temperature and salinity gradients of the height range where the second convecting layer will occur.

➢ We are sorry that we are not familiar with the run-down experiment. As we understood from the published papers, including your great work, the interface gets thicker and thicker with time compared to the mixed layer, which means that Nusselt Number ($Nu=H/h_T$)) would be very small. If this is the case, the flow cannot be turbulent. While in the experiments of a linear salt-stratified fluid heated from below, e.g. in Turner (1968), Huppert and Linden (1979) and so on, the Nusselt number is rather large. In the single layer convection, there are different flow dynamics and heat transport laws for non-turbulent and turbulent convection. We are not sure whether the similar situations happen in the convecting layer of diffusive convection, which may worthy for us to study in future.

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For the authors additional information, the influence of rotation on the heat flux across double-diffusive interfaces has been addressed by Kelley (1987), and very recently by Carpenter & Timmermans (2013). They propose that the relevant control on rotation influencing the diffusive convection is the relative thickness of the thermal interface and the

Ekman length.

- Thanks for your information. We are very glad to read your new findings on the influence of rotation.

- In the revised manuscript, we will add the different definitions of boundary layer and the limitation of linear stability in the description of diffusive convection.

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