Heat Content and Steric Height Change in the Pacific Ocean

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***Abstract*- Changes in the heat content and the steric height in the Pacific Ocean were studied by comparing results from ship-based basin-scale repeat hydrographic surveys mainly conducted in the 2000s in and previous surveys conducted mostly in 1990s. The layer from the surface to a depth of 1000 m accounted for 90% of the increased heat content. In this layer, heat content increased in the western Pacific, with large increases in the western Pacific warm pool and near New Zealand, and decreased in the eastern Pacific. In the bottom layers, below 5000 m the heat content increased in almost entire Pacific. There is a notable heat content increase along the pathway of Lower Circumpolar Deep Water and we can also see the trend toward the northwest. The steric height below 2000 dbar increased in the western Pacific and decreased in the eastern Pacific. The largest increase was seen in the Southern Oceans and as well as the western boundary region off the coast of Japan.**

I. INTRODUCTION

Since the ocean could absorb most of the increased heat trapped by greenhouse gases [1], knowledge on the change in heat content of the ocean is crucial for understanding global warming and for evaluating the reliability of climate models. Recent studies have shown warming of the ocean since the late 1990s. For example, reference [2] estimated the increase in heat content in the upper layer (o to 700 m) of the global ocean to be equivalent to a net input of 0.86 W/m^2 between 1993 and 2003. Reference [3] estimated the heat content increase of the global ocean from the surface to 3000 m is equivalent to a net input of 0.2 W/m^2. Warming in the Pacific has been shown not only in the upper layers of the ocean but also in the deep layers, those are, warming of the modified North Atlantic Deep Water in deep passages of the deep western boundary current in the Samoa Passage of the south Pacific [4] and deep water warming in the Wake Island Passage of the north Pacific [5], deep water warming in the north Pacific along 47°N [6], deep water warming along the pathway of LCDW [7], and deep water warming in the Pacific [8]. The mechanism behind this is not clear, but this warming in the Pacific could suggest a change in the Antarctic overturn circulation [7]. Recently estimation of eat content change on a basin scale was made in the Pacific by comparing by comparing results from ship-based basin-scale repeat hydrographic surveys mainly conducted in the 2000s in and previous surveys conducted mostly in 1990s [9]. In this study, we introduce such estimation of a basin scale heat content change in the Pacific and discuss detail in the consequent steric height change.

II. METHOD

To obtain an accurate picture of ocean circulation and its transport of heat and freshwater, land-to-land global hydrographic data were gathered in the World Ocean Circulation Experiment (WOCE) Hydrographic Program (WHP) in the 1990s. In the 2000s, reoccupations of a subset of the WHP hydrographic sections have been carried out by the Climate Variability and Predictability (CLIVAR) program along with the International Ocean Carbon Coordination Project (IOCCP), as the CLIVAR/Carbon repeat hydrography program, to further refine the WOCE determinations of heat and freshwater transports and to document decadal changes in heat and freshwater transports and in the oceanic inventory of anthropogenic carbon. Reference [9] collected the available hydrographic data from WOCE and revisit cruises and estimated the heat content change as follows.

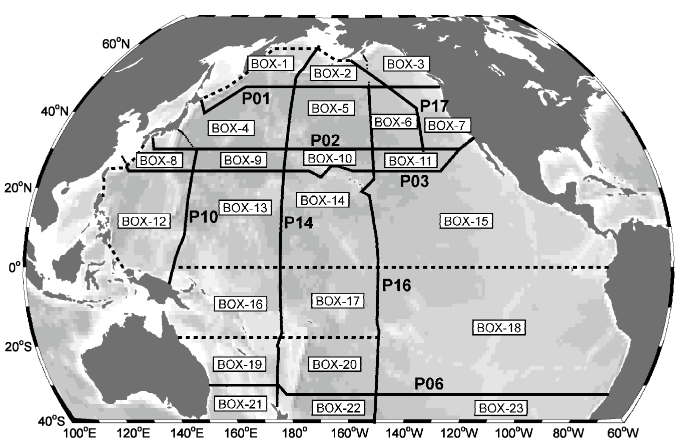

Figure 1. The 23 boxes delineated for the calculation of heat content and steric height change.

The area for heat content calculation was divided into 23 boxes delimited by the intersections of the WHP observation lines in the Pacific Ocean (see Figure 1). Additional lines were added along the equator and along 20°S, west of 150°W, because there were few observations in the low latitudes and a longitudinal gradient in heat content change was expected [9].

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The volume of each box was calculated using 5-minute gridded world elevation data [10].

The change in heat content for each 100-m thick layer in each Box was estimated as follows. The heat content change was averaged over a layer k with 100-m thickness on face i:

$$\Delta HCR(i,k,BOX-n) = \frac{1}{\Delta t}\cdot\frac{1}{A}\cdot\int_{100(k-1)}^{100k}\int_{x1}^{x2}\Delta HeatContent(i,x,z)dxdz \quad (1)$$

$$\Delta HeatContent = \{\rho_2(i,x,z)C_{P2}(i,x,z)\theta_2(i,x,z)-\rho_1(i,x,z)C_{P1}(i,x,z)\theta_1(i,x,z)\} \quad (2)$$

$$A=\int_{100(k-1)}^{100k}(x_2-x_1)\quad dz \quad (3)$$

where subscripts 1 and 2 denote the first and second visits, x and z represents horizontal and vertical direction, respectively. ΔHCR(i, k, BOX-n) is the heat content change rate (W/m^3) of layer k between x_1 and x_2 on face i in BOX-n. The averaged heat content change rate of layer k in BOX-n [ΔHC(k, BOX-n)] is calculated by the equation,

$$\Delta HC(k,BOX-n) = V_1(k,BOX-n)\times\frac{1}{\sum_{i=1}^{I}D_i}\sum_{i=1}^{I}\Delta HCR(i,k,BOX-n)\cdot D_i \quad (4)$$

where I is the number of WHP lines that enclose BOX-*n*, D_i is the width of face *i*, and $V_1(k, \text{BOX-}n)$ is the volume of layer *k* in BOX-*n*. Equation (5) was used to estimate the heat content change for layers with a thickness of 1000 m in each Box:

$$\Delta HCL(l,BOX-n) = \frac{1}{V_2}\cdot\sum_{k=10(l-1)+1}^{k=10l}\Delta HC(k,BOX-n) \quad (5)$$

Heat content increase in the deep layer could cause sea-level rise. Change in the thickness of layer k of each box is estimated by the similar method by [11] as follows;

$$\Delta h_k = \left(\frac{1}{\rho_k+\Delta\rho_k}-\frac{1}{\rho_k}\right)\times\rho_k\times dz \quad (6)$$

where dz is thickness (100 m) of layer k and ρ_k is density averaged in each box. Density change $\Delta\rho_k$ is calculated as a function of thermal expansion coefficient (α) and saline contraction coefficient (β) as follows [12];

$$\Delta\rho_k = -\alpha(\theta,S,P)\times d\theta\times\rho_k + \beta(\theta,S,P)\times dS\times\rho_k \quad (6)$$

where θ, S and P are potential temperature, salinity and pressure averaged in each box and dθ and dS represent change in averaged potential temperature and salinity, respectively. The steric height change rate was obtained by Δhk divided by the interval of observations.

III. Result

Horizontal distributions of heat content change in each layer are shown in Figure 2 [9]. The first layer, from the surface to a depth of 1000 m, accounted for 90% of the increased heat content. In this layer, heat content increased in the western Pacific, with large increases in the western Pacific warm pool and near New Zealand, and decreased in the eastern Pacific. In the bottom layers (see Figure 2), the heat content increased in almost entire Pacific. There is a notable heat content increase along the pathway of Lower Circumpolar Deep Water and we can also see the trend toward the northwest. The heat content in the layer deeper than 4000 m increased throughout most of the Pacific. The heat content increase below 3000 m is calculated to be about 5% of the total increase.

The steric height changes by thermal expansion and by the effect of saline contraction are shown in Figures 3 and 4, respectively. Because upper layer could be strongly affected by seasonal variation, only the estimations below 1000m are discussed here. Reflecting the heat content increase, the steric height is increasing at every level below 1000db. However, when we consider the effect of saline concentration, it is not necessarily increasing in the entire Pacific. Since measurement uncertainty of salinity is greater than that of temperature, the careful consideration is required when we estimate the contribution of deep layer to the steric height change. Figure 5 shows a steric height change considering both effects. The steric height increased in the western Pacific and decreased in the eastern Pacific. The largest increase was seen in the Southern Oceans and as well as the western boundary region off the coast of Japan. The steric height change rate below 700m averaged over the entire Pacific in this estimation was calculated to be 0.3 mm/year, which is consistent with previous studies such as [2] and [13].

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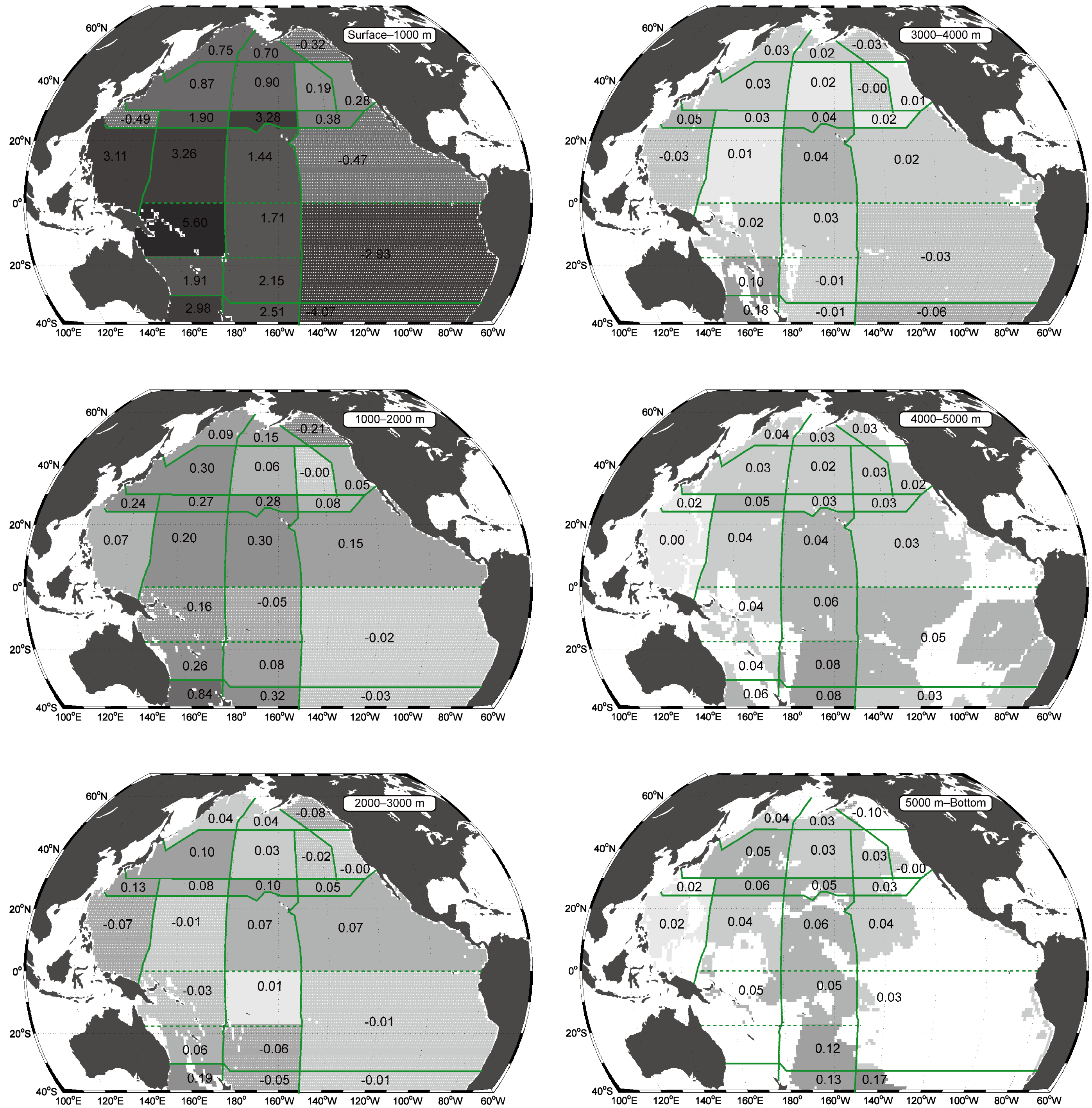

Figure 2. Horizontal distribution of heat content change in the Pacific Ocean in layers of 1000-m thickness. Solid and hatch indicate increasing and decreasing heat content, respectively. The value within each box represents the heat input per volume required ($\times 10^{-3}$ W/m^3) to produce the changes in each box.

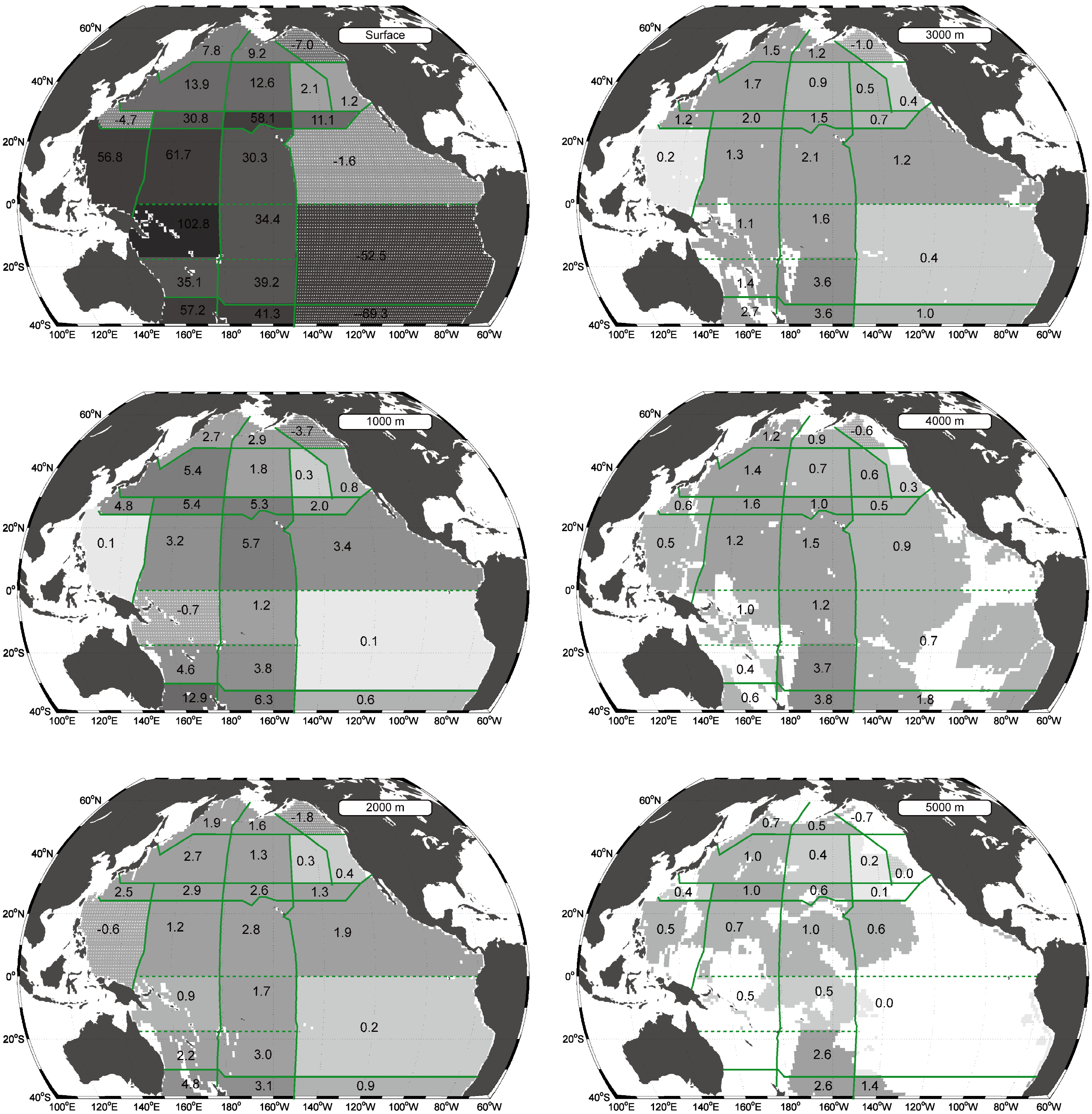

Figure 3. Horizontal distribution of steric height change due to thermal expansion in the Pacific Ocean in layers of 1000-m thickness. Solid and hatch indicate increasing and decreasing heat content, respectively. The value within each box represents steric height change rate (mm / 10-year) to produce the changes in each box.

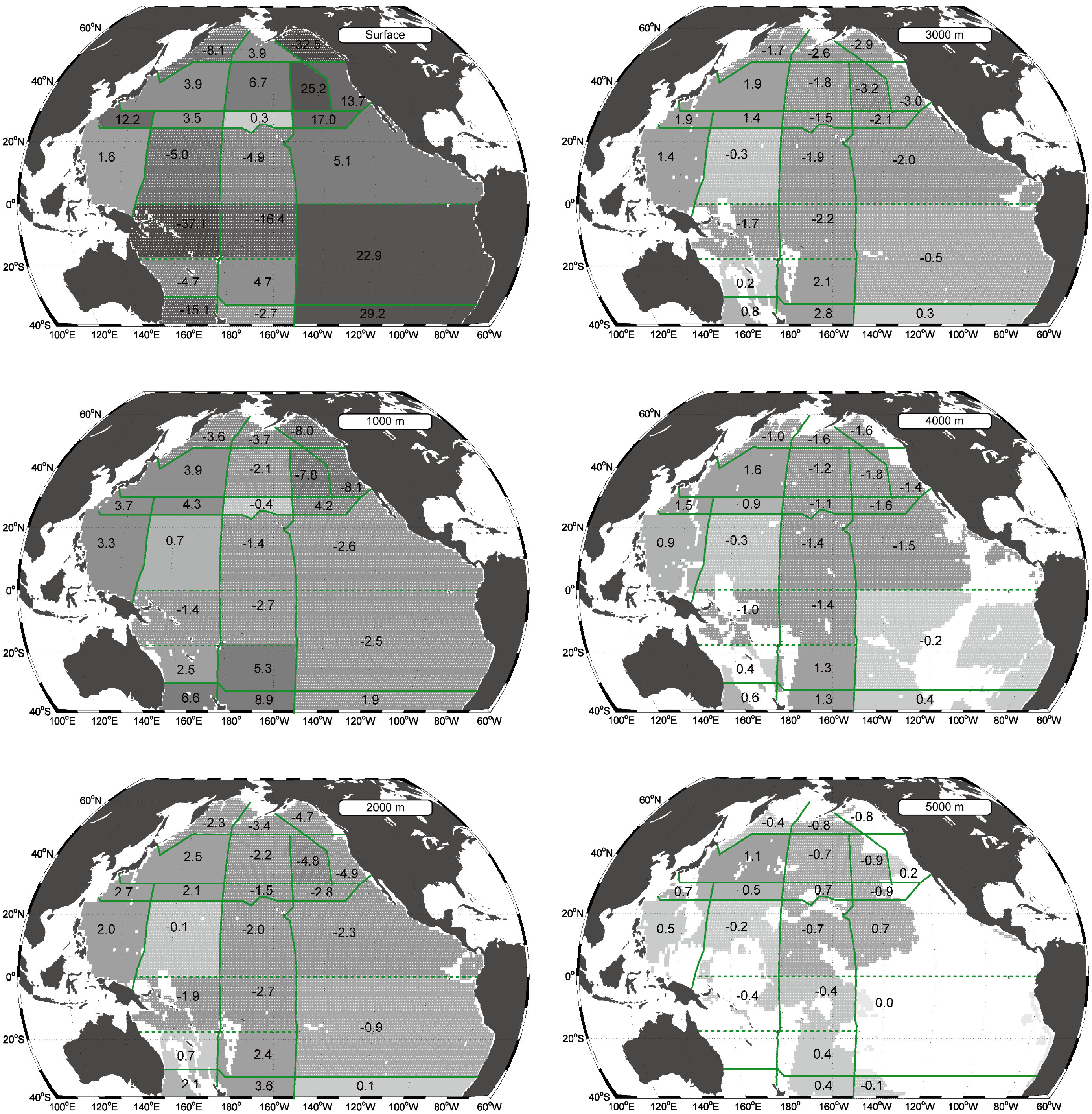

Figure 4. Horizontal distribution of steric height change due to the effect of saline concentration in the Pacific Ocean in layers of 1000-m thickness. Solid and hatch indicate increasing and decreasing heat content, respectively. The value within each box represents steric height change rate (mm / 10-year) to produce the

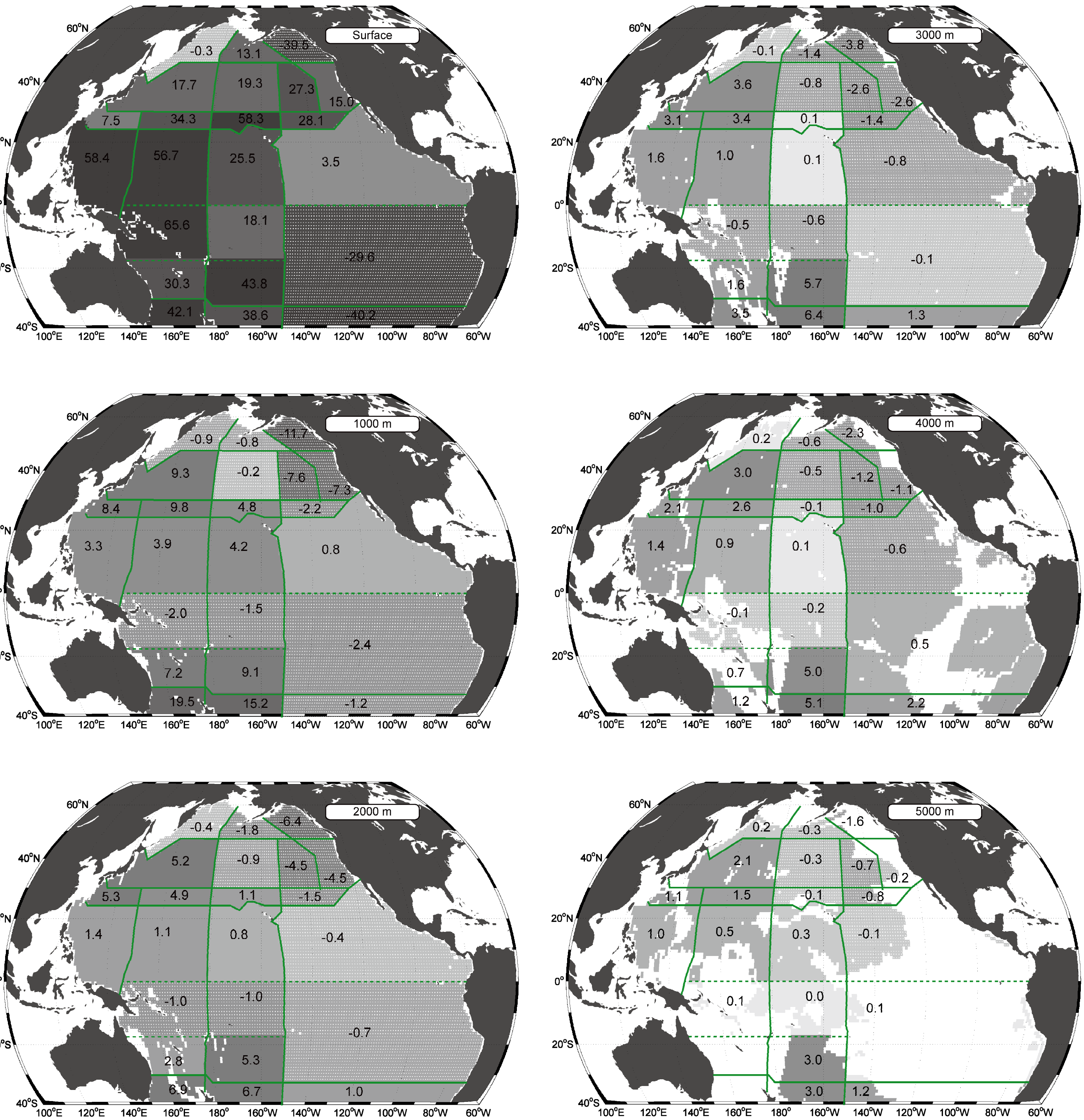

Figure 5. Horizontal distribution of over all steric height change in the Pacific Ocean in layers of 1000-m thickness. Solid and hatch indicate increasing and decreasing heat content, respectively. The value within each box represents steric height change rate (mm / 10-year) to produce the changes in each box.

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