Met Office

Summary of large-scale biases in the global FOAM ocean forecasting system

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Abstract

Time-mean assimilation increments from a one-year hindcast are used to diagnose the main, large-scale drifts in the FOAM global ocean forecasting system. These are compared with time-mean difference fields between a free-running hindcast and the assimilative hindcast. A comparison is made of the biases in Version 0 and Version 1 of the FOAM system.

Contents

1 Introduction

Upgrades to the FOAM[1] ocean forecasting system are usually tested by running one or two year hindcasts and looking at validation statistics to check that the changes to the system have improved or at least not degraded the statistics (Storkey et al 2010). These hindcasts also provide an opportunity to assess the performance of the physical model by examining the way that the model tends to drift away from its initialised state. Biases in the model can be diagnosed using a number of metrics, such as forecast error against analyses, time-mean trends, or time-mean assimilation increments. In this report time-mean assimilation increments are used to diagnose and summarise the main biases in the FOAM system.

Figure 1 illustrates the method schematically. The FOAM system runs on a 24-hour assimilation cycle. Observations valid for the current 24-hour cycle are combined with the model background field to produce an analysis and a set of increments to the model fields. The increments are nudged in to the model over the 24-hour IAU[2] step. The increments are therefore indicative of the difference between the constrained model and a free-running forecast as illustrated in the figure. Where the model errors are random then they will be equally likely to be positive or negative and the time-mean increments will tend to zero, but where there is a model bias there will be a nonzero time-mean increment with the opposite sign to the bias. This kind of analysis has been described in the context of atmosphere models by, for example, Rodwell and Palmer (2007) and Klinker and Sardeshmukh (1992).

The method is good for diagnosing biases that tend to build linearly with time, such as biases due to errors in the model mixing parametrisations or biases due to errors in the surface fluxes. It will not capture biases that develop over longer timescales, such as biases due to advection of non-local errors or nonlinear effects. This report also shows results from a free-running hindcast initialised at the same point as the standard hindcast. Time-mean differences between the fields from the free-running model and the fields from the standard hindcast give an indication of model biases, but will include the short-term, linear biases shown by the time-mean increments and also the long-term, nonlinear biases.

Results presented in the main section of the report are taken from 2-year hindcasts for 2007 and 2008[3] using Version 1 of the FOAM global system. The hindcasts were initialised in October 2006 from a restart from hindcast of a previous version of the system and spun up with assimilation for three months prior to the start of the assessment period on 1st January 2007. There is also a comparison of these results with results from the previous Version 0 of the FOAM system. A full description of FOAM Version 0 can be found in Storkey et al (2010). The upgrade to Version 1 involved some minor model changes and changes to the error covariances and mean dynamic topography in the assimilation scheme. A summary of the Version 1 changes is given in the Appendix.

[1] Forecasting Ocean Assimilation Model

[2] incremental analysis update

[3] Most annual mean fields shown only include the 2007 part of the hindcast since the 2008 hindcast was not finished at the time of writing.

FOAM assimilates in-situ temperature and salinity profile data, satellite SST[4] data, satellite SLA[5] data and satellite sea-ice concentration data. A bias analysis based on time-mean increments is limited to those variables that are assimilated into the model, so this report focusses for the most part on temperature and salinity biases, with a brief summary of sea-ice concentration errors. Note that the mesoscale signal in the SLA data is assimilated into the model using the method of Cooper and Haines (1996), in which the thermocline is lifted or lowered to effect the required changes in the SLA field. This results in temperature and salinity increments over depth. The increments presented in this report are the total increments including the contribution from temperature and salinity data and from the Cooper and Haines scheme.

The report is organised as follows. Section 2 gives a description of the main biases found in the Version 1 system broken down by geographical region. In Section 3 there is some discussion of the differences in the biases found in Version 0 and Version 1. Section 4 gives conclusions and directions for future work.

2 Description of biases

Figure 2 shows annual mean temperature increments for 2007, the first year of the hindcast, and Figure 3 shows the annual mean difference in temperature between the free run and the assimilative run for 2007. Figures 4 and 5 show the same quantities for salinity. There is some similarity in the patterns between the mean increment fields and the free minus assimilative difference fields. Where there are linearly growing errors in the model, one would expect to see areas of warm temperature increments corresponding to cold biases as shown by the difference fields. The correspondence will be imperfect because the daily increments are correcting for short-term (fast physics) errors, whereas the difference fields show errors that evolve on timescales up to a year.

For the temperature there are widespread cold increments in the tropics that are matched by a warm error in the difference fields, as well as warm increments on the equator in the Atlantic and east Pacific which show as cold errors in the difference fields, to take two examples. For the salinity there are salty increments near the surface in the Indian Ocean and western Pacific which are matched by fresh errors in the difference fields.

There are also striking differences in the patterns of the increments and difference fields particularly at the surface. There are large, cold temperature increments south of the Cape of Good Hope and off the east and west coasts of North America which are unmatched by anything in the difference fields. In the salinity fields, there are large, fresh increments in the eastern and central tropical Pacific and the tropical Atlantic which have no corresponding salty errors in the difference fields. Cross sections (not shown) indicate that these increments are very shallow, confined to the top $2m$ of the water column. They therefore represent relatively small changes in the heat and salt

[4] sea surface temperature
[5] sea level anomaly

content and are probably mixed away by model processes. These increments come from in situ measurements and at least for the temperature there must be a question mark over the quality of the observations since they are inconsistent with the large amount of (bias-corrected) satellite observations which are being assimilated. More investigation of the way that the assimilation scheme is working in these areas is required before these increments can be said to indicate biases in the model.

The following sections describe the main biases region by region.

2.1 The Tropics

2.1.1 Equatorial cold bias

The annual mean temperature increments in Figure 2 show a tongue of warm increments (cold biases) along the equator in the Atlantic and eastern Pacific in the surface and 10m plots. This pattern is reminiscent of “cold tongue” biases seen in the equatorial Pacific in coupled climate prediction models (eg. Misra et al 2008). Examination of cross section plots of monthly-mean increments (not shown) indicates that the biases in the Pacific extend to the top of the thermocline and appear to be dependent on the state of the ENSO[6] oscillation. For most of the hindcast period (2007-2008) the Niño 3.4 index was negative, indicating La Niña conditions with cold SST anomalies in the eastern Pacific. During La Niña conditions the increments along the equator in the eastern Pacific are positive, showing cold biases. However, there were El Niño conditions at the start of the period and during this time the increments in this region tend to be negative, indicating warm biases. A longer timeseries would be required to establish that this was a robust pattern.

The annual-mean difference fields for the temperatures, shown in Figure 3 show cold biases along the equator in the Pacific and the Atlantic as one would expect. The correspondence between the difference fields and the mean increments is not exact in the Pacific: the largest warm increments are in the eastern Pacific, whereas the biggest cold biases as indicated by the difference fields are in the central Pacific. This is a region where advection is important and there are long timescale variability patterns (ENSO), so as discussed in the Introduction, the correspondence between the mean increments and the annual-mean difference fields is likely to be imperfect.

2.1.2 Shallow warm bias

There is a shallow warm bias in the tropics in the near surface layers down to about 30m. It is widespread in the tropics in all three basins. It is clear in the free minus assimilative difference plots in Figure 3 and shows up as cold increments in Figure 2. Figure 6 shows cross-equatorial sections of the annual-mean temperature biases at three locations in the Pacific, Atlantic and Indian Oceans and Figure 7 the corresponding free minus assimilative difference fields. The shallow warm bias (cold increments) is clear in all three sections, centred on the equator and extending to varying

[6] El Niño Southern Oscillation

depths between 10m and 60m. Examination of monthly-mean fields (not shown) indicates that while there is some seasonal variation, the warm bias is fairly persistent throughout the year.

The bias seems likely to be due to errors in the vertical heat transport, either a problem with the heat fluxes at the surface or a problem with the near-surface vertical mixing. A vertical mixing problem (in this case too little mixing down from the surface layers) would be indicated by a dipole pattern in the vertical with warm biases (cold increments) near the surface and cold biases (warm increments) deeper in the water column. There is some indication of this pattern away from the equator in the cross sections in Figures 6 and 7.

Note that the large increments visible in the region of the equatorial undercurrents in Figure 6 are extremely variable from month to month and so seem to be connected with seasonal variability rather than short time-scale vertical processes.

2.1.3 Surface fresh bias

The free minus assimilative difference plots in Figure 5 show large-scale fresh biases at the surface and at 10m in the tropical Indian Ocean, western Pacific and tropical Atlantic. Examination of cross-sections (not shown) shows that these fresh biases are about 50m deep in the Indian Ocean and Pacific, and about 20m deep in the Atlantic. The Indian Ocean and western Pacific cold biases are matched by annual-mean saline increments, which are visible in Figure 4. In the Atlantic the situation is more complicated with a mix of saline and fresh increments near the surface. The "warm pool" errors in the region of Indonesia seem likely to be connected with a known bias to too much rainfall in that region in the NWP model (Shelly 2011).

As already noted in Section 2, the shallow fresh increments in the central and eastern tropical Pacific do not leave an imprint on the free minus assimilative difference fields, and are probably mixed away by the model.

2.2 Mid latitudes

2.2.1 Seasonal thermocline

There are biases associated with the seasonal thermocline in northern mid-latitudes. Figure 8 show monthly-mean temperature increments for August 2007 and August 2008 along 50N sections in the Pacific and the Atlantic. There are large increments associated with the seasonal thermocline at around 30-40m in the Pacific and slightly deeper in the Atlantic. In the Pacific there is a clear dipole pattern for both years, with warm increments in the upper thermocline and cold increments in the lower thermocline. This indicates that the assimilation is trying to sharpen the thermocline which is consistent with there being too much mixing in the model. Note that while the seasonal thermocline dipole is consistent between the two years, the increments at the surface are different: cold increments/warm bias in 2007 and warm increments/cold bias in 2008.

While there are clearly increments associated with the seasonal thermocline in the Atlantic, the pattern is less clear and less consistent between the two years. Northward advection of subtropical waters by the North Atlantic Drift probably complicates the picture in the Atlantic, whereas advection in the North Pacific is less significant. In the western Atlantic in 2007 there is a dipole pattern similar to that found in the north Pacific.

The Pacific dipole error in the seasonal thermocline is very similar to a bias found by Shelly et al (2011) in short-timescale forecast experiments with a coupled model, the ocean component of which was similar to that used in FOAM. In Shelly et al, the thermocline mixing error leads to a drift in the SST. In the FOAM system this is not the case because there is a Haney forcing term (Haney 1971) which tends to constrain the forecast SST to the analysed SST.

2.2.2 Near-surface fresh biases

Figure 5 shows the development of near-surface fresh biases at mid-latitudes in the north Atlantic and north Pacific (in addition to the fresh biases in the tropics already described). A cross-section view along 50N in the Pacific, shown in Figure 9, shows that the fresh biases cover roughly the top 50m and are matched by salty increments. In the eastern half of the section there are salty biases/fresh increments further down in the water column. As well as the annual-mean plots, a timeseries of monthly-mean difference plots is given, showing that the fresh bias develops in a strikingly uniform way along the whole section, starting at the surface and gradually deepening. The development of the biases in the north Atlantic (not shown) follows a very similar pattern.

The north Pacific along this section has a fresh layer at the surface with a sharp halocline just below 100m. The near-surface fresh bias is tending to sharpen and raise the existing halocline. This bias was not present in the FOAM Version 0 system and may be connected with changes in the TKE scheme and the Haney forcing term between Version 0 and Version 1 as discussed further in Section 3.1.

2.2.3 Gulfstream

Examination of Figures 2 to 5 show areas of large mean increments and free minus assimilative differences in both temperature and salinity fields associated with the Gulfstream and Kuroshio extensions. The pattern of biases in the Gulfstream is very coherent, especially at 110m and 320m, with cold and fresh increments north of the front and warm and salty increments south of the front. The pattern is shown up more clearly in Figure 10 which shows cross sections across the Gulfstream extension at 60W. For both temperature and salinity there is a dipole pattern in the mean increments centred on the Gulfstream front. A similar (opposite) pattern is seen in the difference fields, but the cold/fresh biases to the south of the front extend further south than the warm/salty increments, suggesting that biases may be originating near the Gulfstream front and then spreading laterally through diffusion or advection.

The dipole pattern extends over a large depth range, between 250m and 1200m for the temperature fields, and between 250m and 750m for the salinity fields. Closer to the surface the pattern is obscured by surface effects. For the salinity fields the horizontal dipole pattern breaks down below 750m and there is a vertical dipole pattern centred on 750m depth. Monthly mean plots (not shown) show that there is a lot of seasonal variability in this pattern.

As discussed in previous sections, the dipole pattern is consistent with the model mixing too much across the Gulfstream front. However, since the Gulfstream extension transports a core of warm, salty water, this kind of pattern would also be consistent with a north-south positional error in the Gulfstream front representation if the model had a Gulfstream front that was too far north and the assimilation was correcting for this. If the cold/fresh biases in the centre of the gyre really are connected with the Gulfstream, this would tend to suggest a mixing error that was changing the large-scale water mass properties.

2.2.4 North Atlantic salinity maximum

Figure 11 shows sections along 15W illustrating biases associated with the North Atlantic salinity maximum at 1000m. The annual-mean salinity increments show a clear tripole pattern centred at the depth of the salinity maximum, which indicates that the assimilation is trying to sharpen the vertical gradients. There are salty increments at the depth of the maximum and fresh increments above and below. However, the free minus assimilative difference field does not show the same pattern, perhaps indicating that the model is not retaining the assimilation increments in this region.

2.3 High latitudes

2.3.1 Southern Ocean warm bias

The model tends to warm in the surface layers in the Southern Ocean south of the Antarctic Circumpolar Current (ACC). This can be seen clearly in Figure 3 at the surface and also at 10m and 110m. Meridional cross sections of the free minus assimilative difference fields for three locations are shown in Figure 7. Again the warming trend south of the ACC can be clearly seen, extending from the surface to about 200m in the Indian and Atlantic sector plots and deeper in the Pacific sector. For the Indian sector, there is some indication of dipole patterns associated with the ACC fronts, similar to those seen for the Gulfstream.

Cross sections of the annual-mean temperature increments shown in Figure 6 show cold increments south of the ACC that correspond very well to the pattern of differences between the free and assimilative runs, showing that the bias is being controlled by the temperature assimilation, even though this is not obvious from the horizontal plots of temperature increments (Figure 2). Again there is some indication of a dipole pattern across the ACC fronts but this is not completely clear.

While the warm bias is clear in the annual mean plots, inspection of monthly mean fields (not shown) indicates that it mainly occurs in the austral summer. Experiments with coupled models based on NEMO show similar warm biases at the surface in the Southern Ocean (Graham et al 2010). In the context of the coupled model this is thought to be due in part to errors in atmospheric models which tend to have too little cloud over the Southern Ocean and therefore to allow too much short-wave radiation to impinge on the ocean.

2.3.2 Sea ice biases

The FOAM system assimilates sea-ice concentration data from SSM/I satellite data[7], but the ice thickness is unconstrained by assimilation. Figure 12 shows annual-mean sea-ice concentration increments for 2007 as well as monthly-mean increments from the ice-growth and ice-melt seasons for both hemispheres.

The ice-melt season plots (June for the Arctic and December for the Antarctic) show that the sea-ice tends to melt too quickly in the spring and the assimilation corrects this by inserting positive ice increments. For the Arctic this happens around the ice edge, but for the Antarctic this occurs over the whole ice area. For the Antarctic, there is no clear pattern of biases in the ice-growth season, so the annual mean shows positive increments indicating that over the annual cycle the ice tends to melt away. The ice-growth season in the Arctic shows negative increments (too much ice) in the East Greenland Current and Baffin Bay. In the East Greenland Current there are also positive increments next to the coast and further south showing that the model tends to spread the ice too far out from the coast and tends not to advect it far enough south. This may be caused by the model having insufficient resolution to adequately represent the East Greenland Current. There also appears to be too much southward advection of ice along the Labrador coast.

Figure 5 shows large near-surface salinity drifts in the Arctic. There are no corresponding salinity increments in Figure 4, so the drift is probably due to the sea-ice assimilation. The assimilation of sea-ice concentration alters the surface salinity properties by inserting fresh increments where there is ice melting and saline increments where there is ice growth, in order to conserve fresh water.

3 Comparison of FOAM Version 0 and FOAM Version 1 results

All the results shown in Section 2 have been from Version 1 of the FOAM system, which was implemented in the Met Office Operational Suite in October 2010. In this section we show some comparisons with the previous version of the system - Version 0. A summary of the main differences in the physical model and assimilation scheme between Version 0 and Version 1 is given in the Appendix.

Figures 13 and 14 show annual-mean increments for 2007 for temperature and salinity from hindcasts of the FOAM Version 0 system. These should be compared with Figures 2 and 4. Many of the patterns are similar between Version 0 and Version 1, but there are some significant differences

[7] Special Sensor Microwave/Imager data supplied by the EUMETSAT ocean Sea Ice Satellit Application Facility (OSI-SAF)

which are described in the next two sections.

3.1 Near-surface temperature and salinity biases

There is a significant difference in the surface and 10m temperature increments. At Version 0 there are widespread warm increments, indicating a cold bias, between 30N and 70N. These warm increments are much reduced or absent at Version 1. Examination of cross sections (not shown) shows a dipole structure to the increments with warm increments in the top 20m and cold increments below this down to 70m. The magnitude of both the warm and the cold increments is reduced at Version 1 compared to Version 0 suggesting that a vertical mixing error has been reduced at Version 1.

One of the model changes at Version 1 was an upgrade to the TKE[8] vertical mixing scheme. The discretisation has been reformulated to make the shear and buoyancy production terms energy-conserving. Burchard (2002) found that the old discretisation gave spurious shear production of TKE, resulting in too much vertical mixing. Figure 15 shows results of sensitivity experiments done to investigate the impact of the change to the TKE scheme in the FOAM system. The Version 1 hindcast was rerun for one month (August 2007), initialised from the standard hindcast, once with the old TKE scheme and once with the new TKE scheme. Note that Haney forcing of the surface heat flux was omitted in both experiments. The difference in the plots from the two experiments is very reminiscent of the difference between the Version 0 and Version 1 biases noted above. With the old version of the scheme, there are widespread warm increments (cold biases) in the northern hemisphere and a vertical dipole of errors in the North Pacific, both of which are much reduced using the new version of the scheme.

This strongly suggests that much or all of the improvement in these biases seen at Version 1 is due to the upgrade to the TKE scheme. Another change which may have had some impact is a change to the Haney forcing of the surface heat flux. At Version 0, the Haney forcing term used a climatological SST field as the reference SST field. 2007 had warmer than average SSTs in the northern hemisphere, so the relaxation to climatological SST was tending to make the model SST too cold. At Version 1, the reference SST field is the OSTIA daily analysis (Donlon et al 2011), used as a surface boundary condition by the NWP model.

There are also differences in the near-surface salinity biases in mid-latitudes. These do not show up in the comparison of Figures 14 and 4 because of the choice of colour scale. However, they are clear in Figure 16, which shows the Pacific 50N cross-section of free minus assimilative differences for salinity for FOAM Version 1 and FOAM Version 0. The striking near-surface fresh bias described in Section 2.2.2, which is present along the whole section at Version 1 is not present at Version 0. Also shown in Figure 16 are salinity anomalies from climatology from the free-running hindcasts for Version 1 and Version 0. The Version 1 anomalies look very similar to the Version

[8] turbulent kinetic energy

1 free minus assimilative difference fields and the near-surface fresh anomalies are again absent at Version 0. This indicates that the change at Version 1 is due to changes in the physical model rather than changes in the assimilation scheme. The differences between Version 0 and Version 1 are consistent with there being less vertical mixing at Version 1. Hence it may be that this difference has also been caused by the upgrade to the TKE scheme noted above. Since there is good evidence that the upgrade to the TKE scheme is an improvement, it may be in this case that spurious mixing produced by the old version of the TKE scheme was compensating for another bias in the model at Version 0.

3.2 Deep increments

Another systematic difference between Version 0 and Version 1 can been seen in the 320m temperature increments, and also to a lesser extent in the 320m salinity increments. The magnitude of the mean increments at this depth (and at depths down to 1500m - not shown) is greater in Version 1 than in Version 0 along the equator and in the subtropical gyres. Figure 17 shows annual mean increments for the equatorial cross-section for Version 1 and Version 0, illustrating this point further. The pattern of the increments at Version 1 is similar to the pattern at Version 0 but the magnitude has increased significantly.

A possible explanation for this may lie with the recalculated error covariances used at Version 1. One of the effects of the new error covariances is that that SLA field is being fitted more closely by the model (Lea 2011). The mesoscale SLA increments are applied to the model by lifting and lowering the water column using the method of Cooper and Haines 1996. This particularly affects the temperatures and salinities at thermocline depths, so the closer fit to the SLA field could result in increased temperature and salinity increments in the thermocline.

4 Conclusions and further work

This report has attempted to summarise the main large-scale biases in the FOAM global physical model using the time-mean assimilation increments from a one-year hindcast as a diagnostic of the model drift away from its initialised state. Because of the use of assimilation increments, the analysis has been restricted to those variables for which observations are assimilated, that is temperature, salinity and sea-ice[9]. Biases have also been diagnosed by examining the time-mean differences between a free-running hindcast and the standard, assimilative hindcast.

As outlined in Rodwell and Palmer (2007), there are two reasons for pursuing this kind of analysis. Firstly, these diagnostics can act as a benchmark for model development. When changes are made to the model, the hindcast and the bias analysis can be rerun to check that the model changes have reduced or at least not increased the biases diagnosed here. This kind of bench-

[9]SLA data is also assimilated but only its effects on the temperature and salinity fields have been examined here

marking analysis for the upgrade from Version 0 to Version 1 was briefly described in Section 3, in which the model changes were found to have reduced some biases (mid-latitude surface temperature biases), increased others (mid-latitude surface salinity biases), but mostly had a neutral impact. Some changes to the time-mean increments are attributable to changes in the assimilation scheme. This highlights the point that ideally one should test model changes using an unchanged assimilation scheme. However, in practice, both the model and the assimilation are upgraded in tandem, and resource constraints often mean that it is not possible to run long hindcasts that test the model and assimilation changes independently.

The second reason for analysing model biases is to act as a starting point for the next cycle of model development. If one can identify the causes of some of the largest biases then one has identified a flaw in the model which one can attempt to correct. The next step therefore is to try to identify the causes of the biases identified in this report. Two possible approaches for doing this are as follows.

(a) In some cases, it may be useful to look at budgets of heat and fresh water. For example, where one has a temperature or salinity bias at the surface the two most likely explanations are errors in the model mixing parametrisations or errors in the surface fluxes. A budget analysis may be able to distinguish between these two possibilities.

(b) Another approach is to look at initial trends. If one can identify the erroneous time-mean trends in the model fields, then one can output trends from the various components of the model (eg. advection, horizontal and vertical mixing) separately and attempt to identify which of these components is primarily responsible for the bias or erroneous trend. There are potentially confounding issues with this approach. One has to be able to separate out the erroneous trend from real trends such as those due to the diurnal or seasonal cycle. Also, compensating errors could make it difficult to separate out the cause of the bias in question.

More generally, it would be useful to look at fields of forecast error against analysis, since this allows one to analyse errors in fields that are only indirectly constrained by the assimilation such as the currents and mixed-layer depth.

There is currently work at the Met Office to move towards a more seamless forecasting system, in which atmosphere and ocean forecasting at short timescales is done using a fully coupled model, and the short-term forecasting system is developed in close step with the system used for seasonal and decadal forecasting and climate prediction. As part of this, Shelly et al (2011) have performed some initial short-range forecasting experiments using a coupled model. Comparison of the drifts found in these experiments with those detailed in this report should also help to shed light on the origins of some of the model errors detailed here.

5 Appendix: Changes in FOAM Version 1 compared to FOAM Version 0

The main science changes between Version 0 and Version 1 of the FOAM system were as follows.

- A new version of the Rio et al.(2005) mean dynamic topography (MDT) is used in the assimilation of sea surface height data. The version used at FOAM Version 1 is CNES-CLS_v1.1.
- The error covariance fields in the assimilation scheme were recalculated and are also seasonally varying at Version 1.
- The version of the NEMO code used was upgraded from version 3.0 to version 3.2
- At Version 1 an upgraded version of the TKE[10] scheme is used. The discretisation of the new scheme has energy-conserving shear and buoyancy TKE production as described in Burchard (2002).
- At Version 0, the Haney forcing term in the surface heat flux used monthly-mean climatological fields for the reference SST field. At Version 1, the Haney forcing term uses the same SST analysis that is seen by the NWP model.
- A bug in the interpolation of the wind flux fields near coastlines has been corrected at Version 1.
- At Version 0, the model was forced with 6-hourly mean NWP fluxes. Version 1 uses 3-hourly mean NWP fluxes.

[10] turbulent kinetic energy

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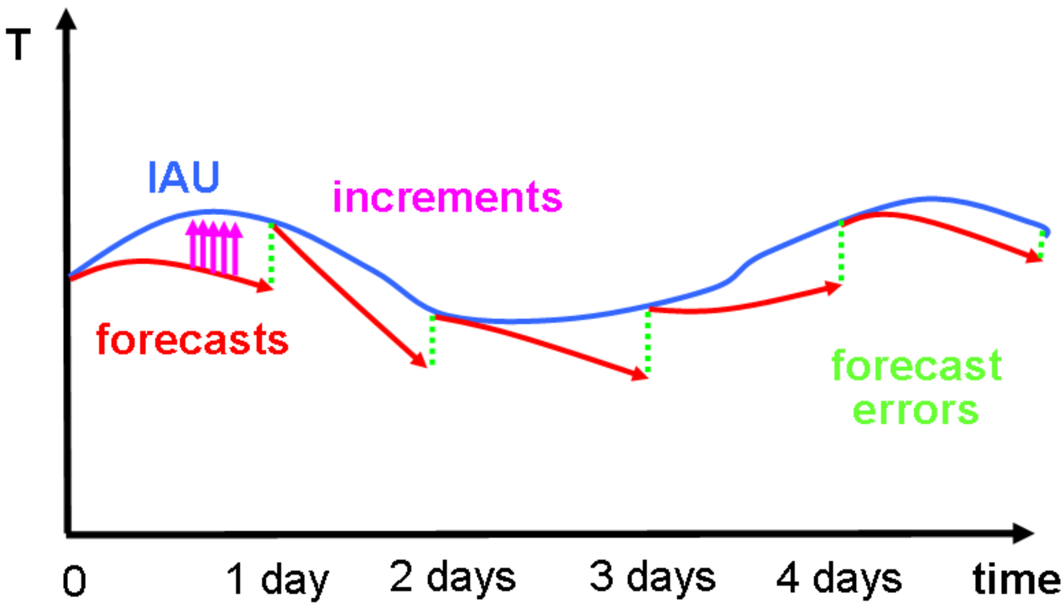

Figure 1: Schematic illustrating how model biases can be diagnosed using time-mean assimilation increments. The blue line represents the evolution of a model variable (say temperature) at a point during the model hindcast. The red lines represent model forecasts that are spun off evey 24 hours and the green dotted lines show the forecast error against analysis. The increments shown in purple are applied over each 24-hour IAU step and also give an indication of the difference between the model hindcast fields and the free-running forecast. In this case the model has a tendency to be too cold, so the time-mean forecast error in temperature would be negative and the time-mean temperature increments would be positive.

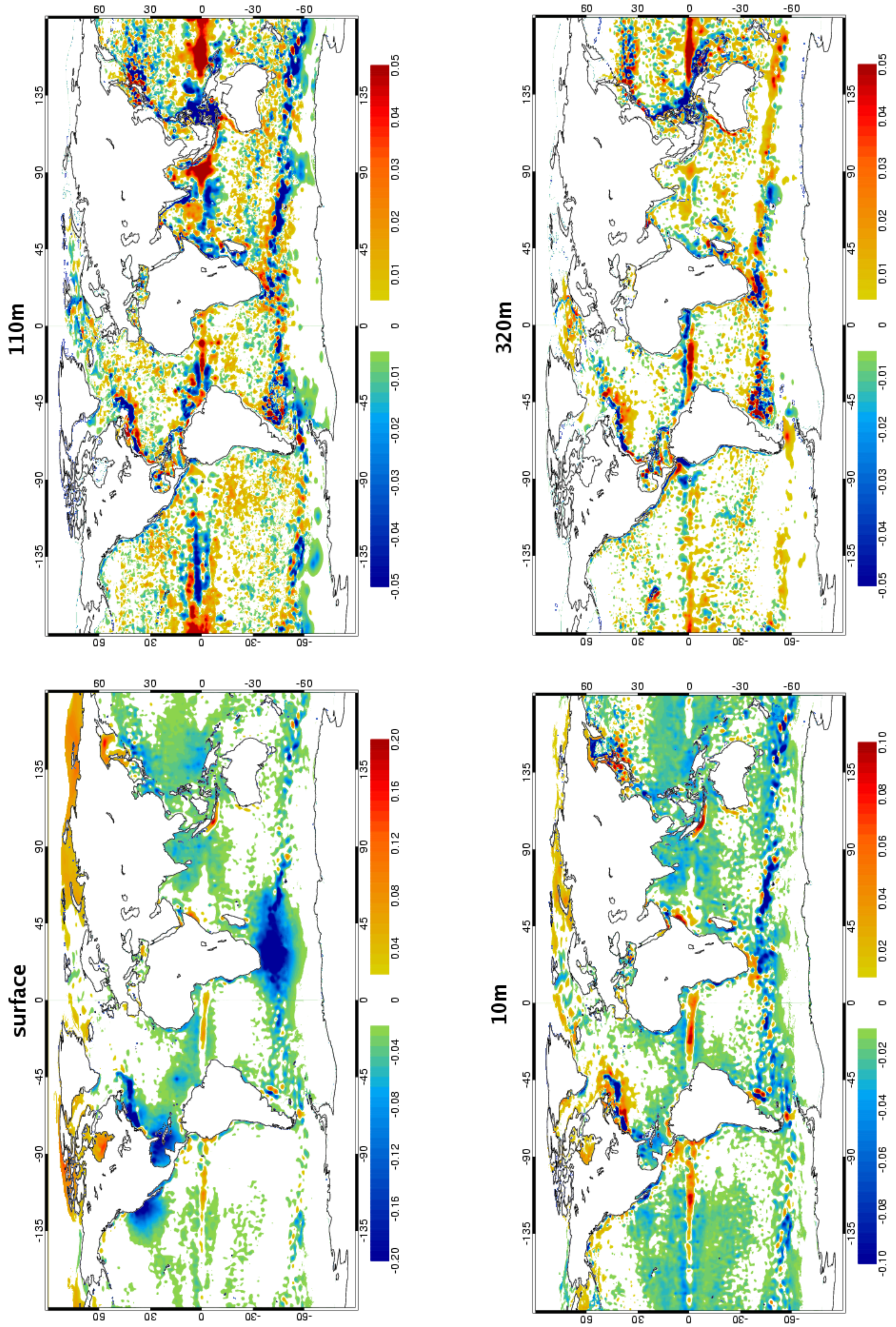

Figure 2: Annual mean temperature increments (K/day) from the FOAM V1 hindcast for 2007

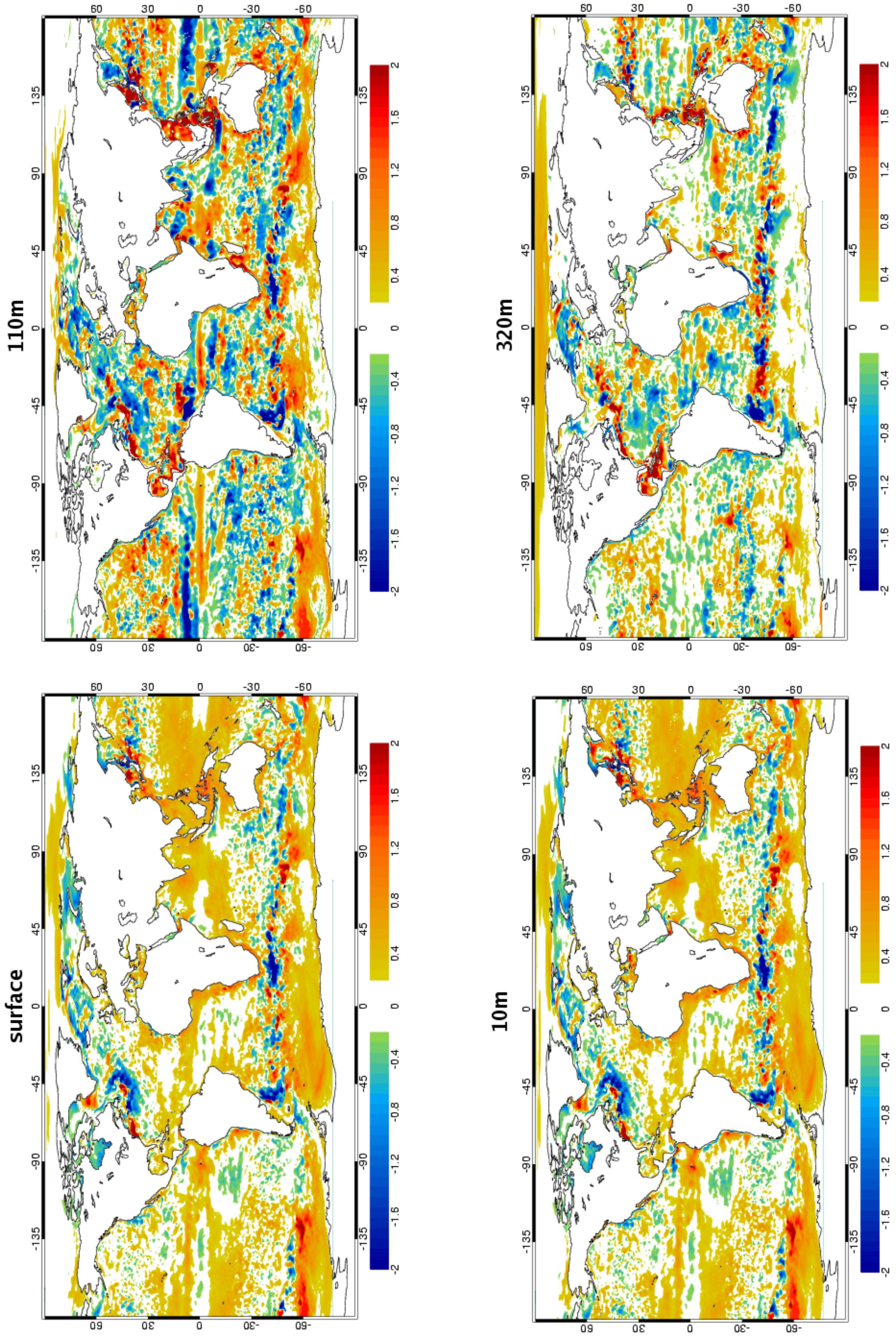

Figure 3: Annual mean temperature differences (K) between the free and the assimilative integrations for the FOAM V1 hindcast for 2007

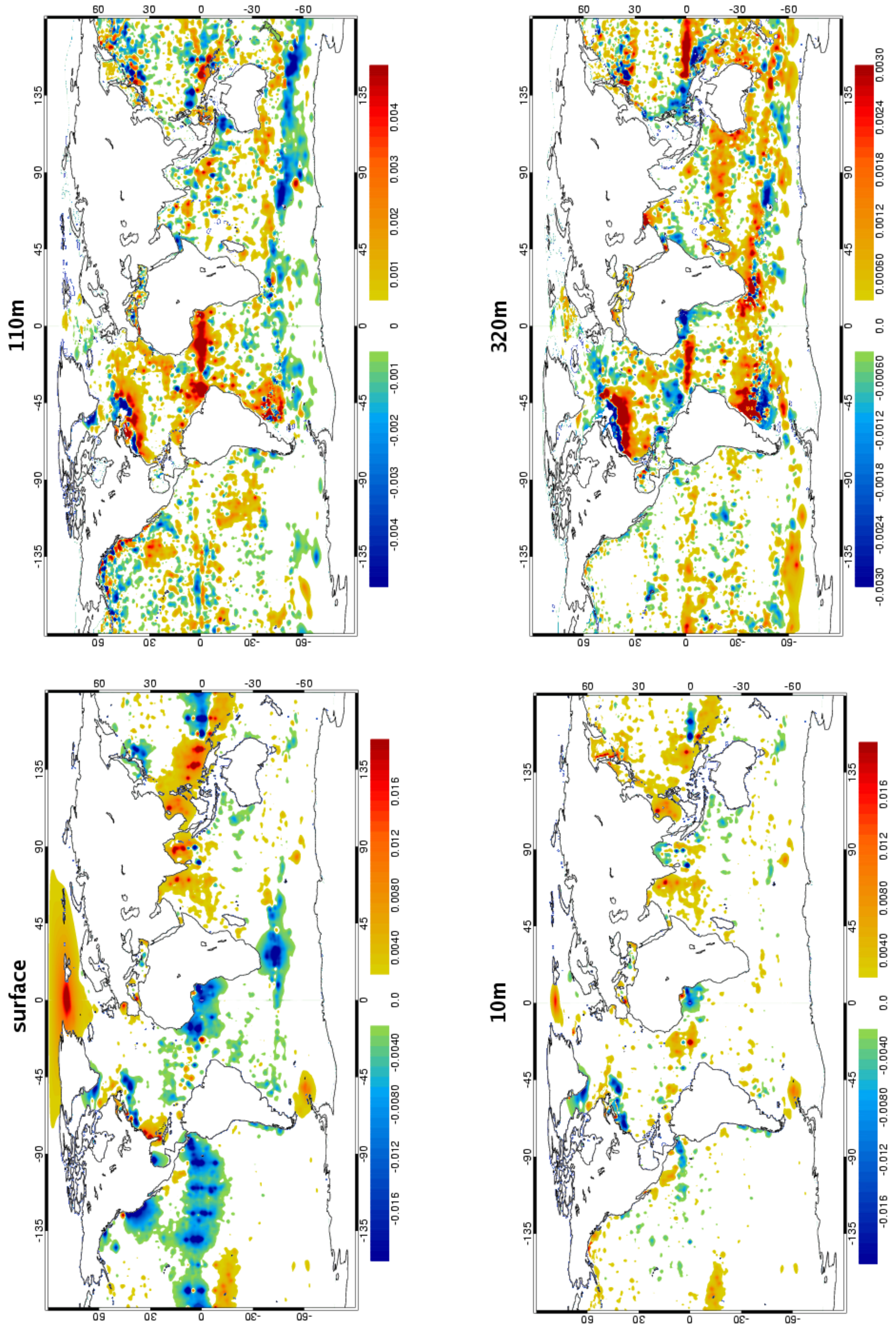

Figure 4: Annual mean salinity increments (psu/day) from the FOAM V1 hindcast for 2007

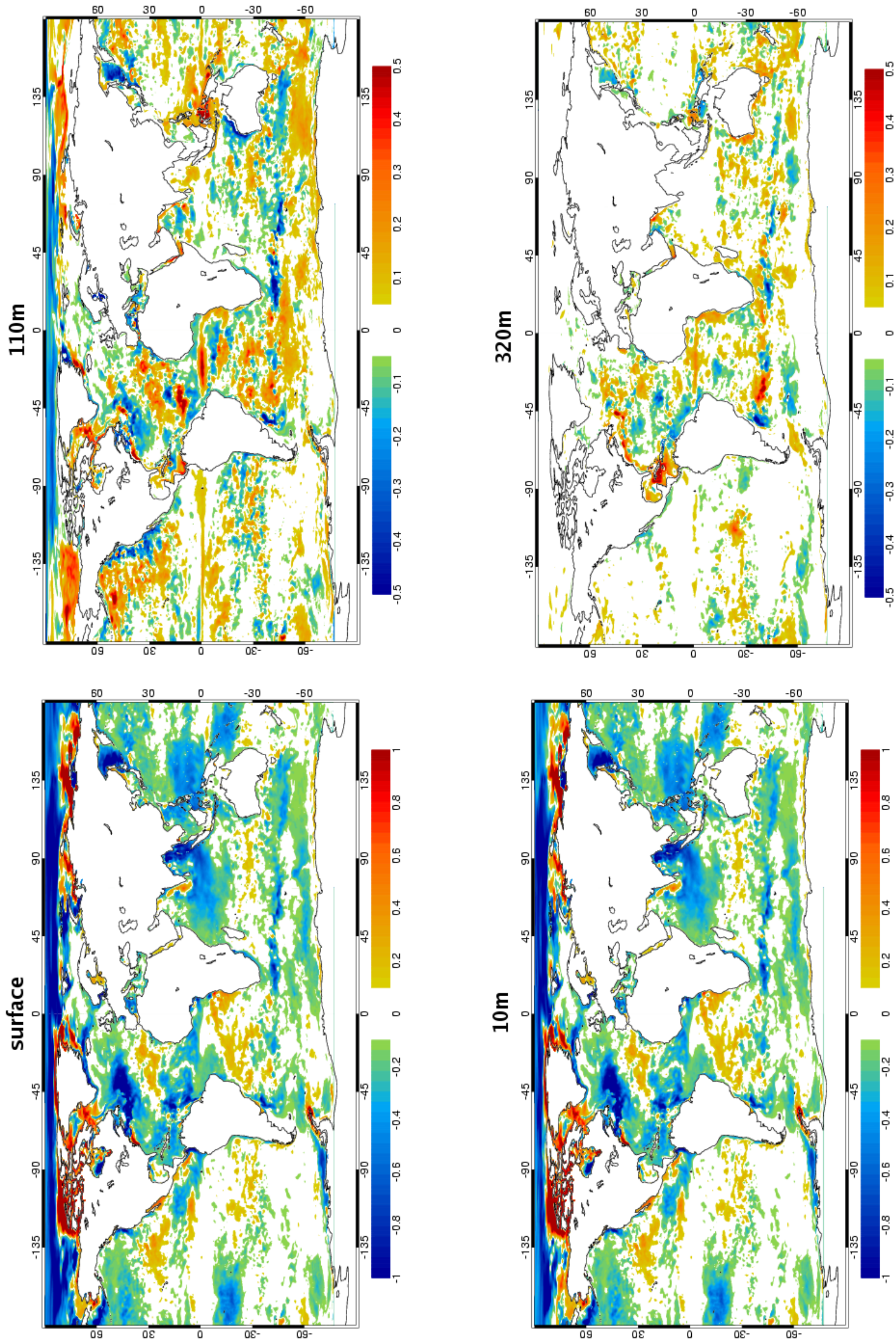

Figure 5: Annual mean salinity differences (psu) between the free and the assimilative integrations for the FOAM V1 hindcast for 2007

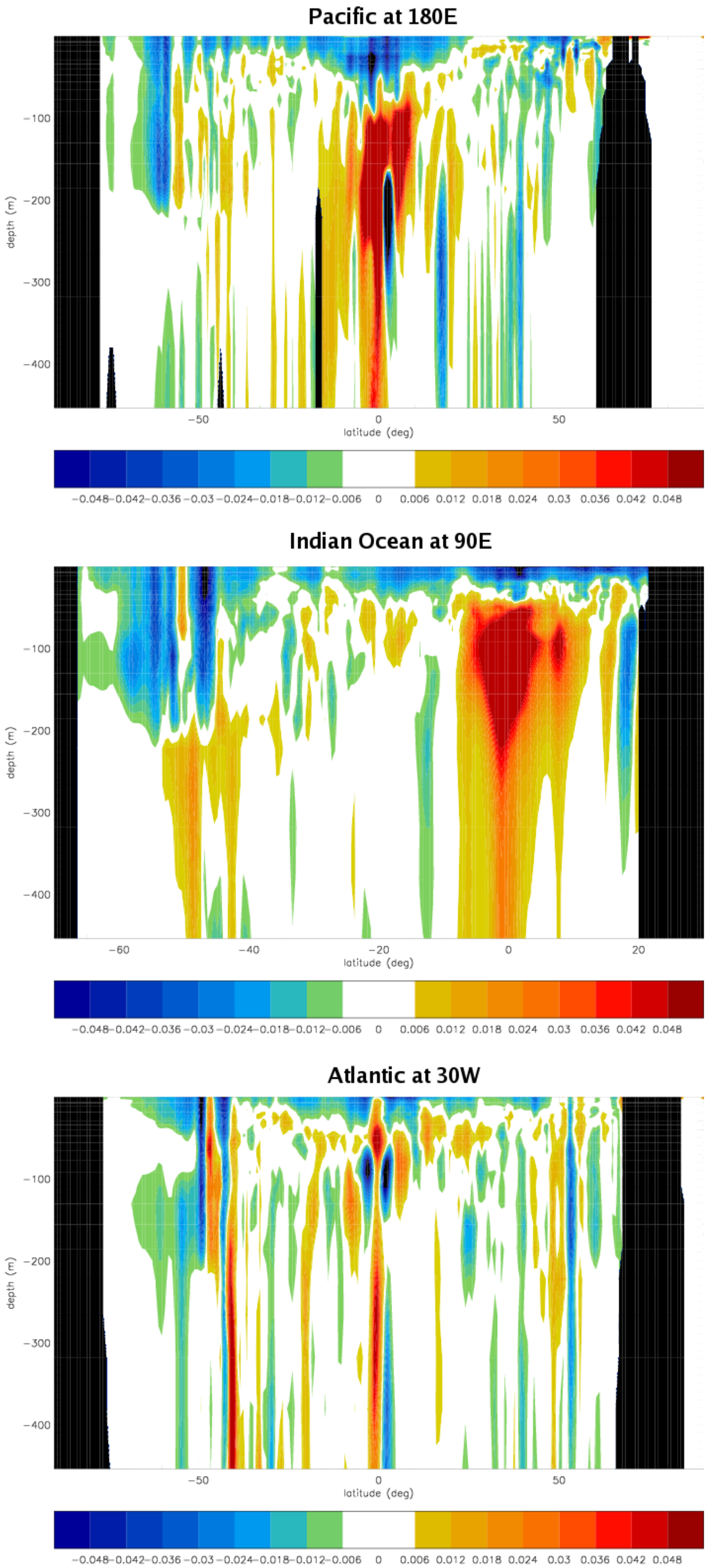

Figure 6: Cross sections of annual mean temperature increments (K/day) for the FOAM V1 hind-cast for 2007

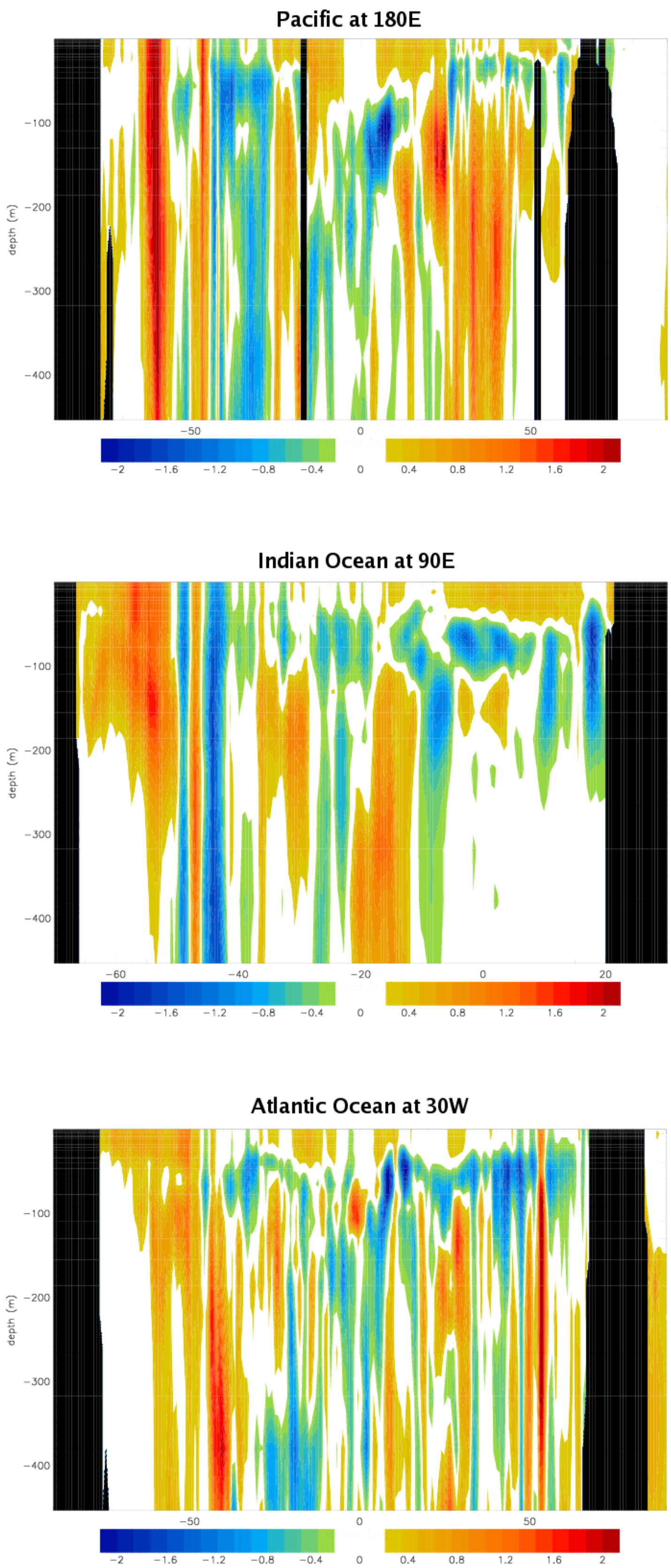

Figure 7: Cross sections of annual mean temperature differences (K) between the free and assimilative integrations for the FOAM V1 hindcasts for 2007

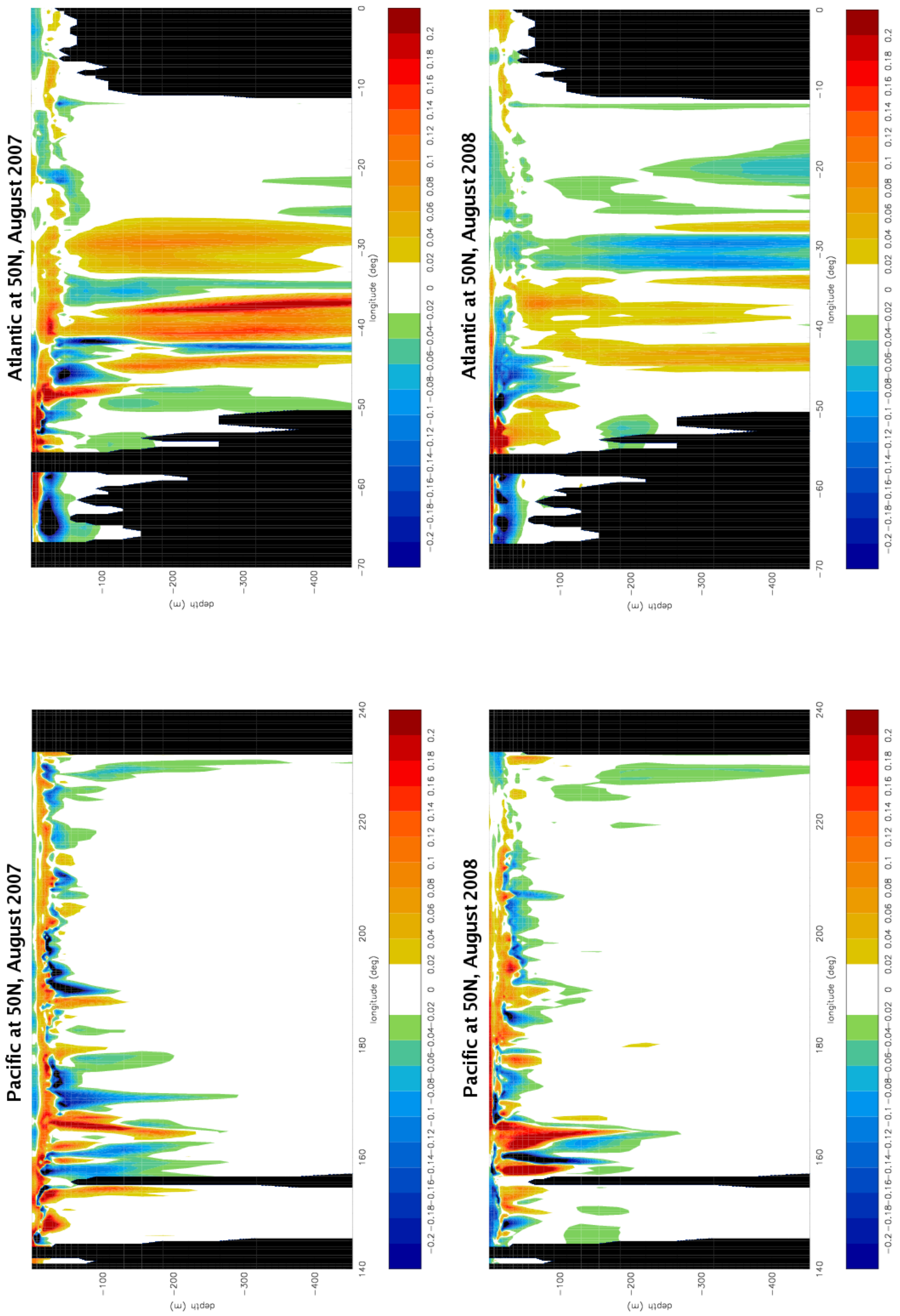

Figure 8: Cross sections of monthly mean temperature increments (K/day) for the FOAM V1 hind-cast for August 2007 and 2008, showing biases centred on the seasonal thermocline.

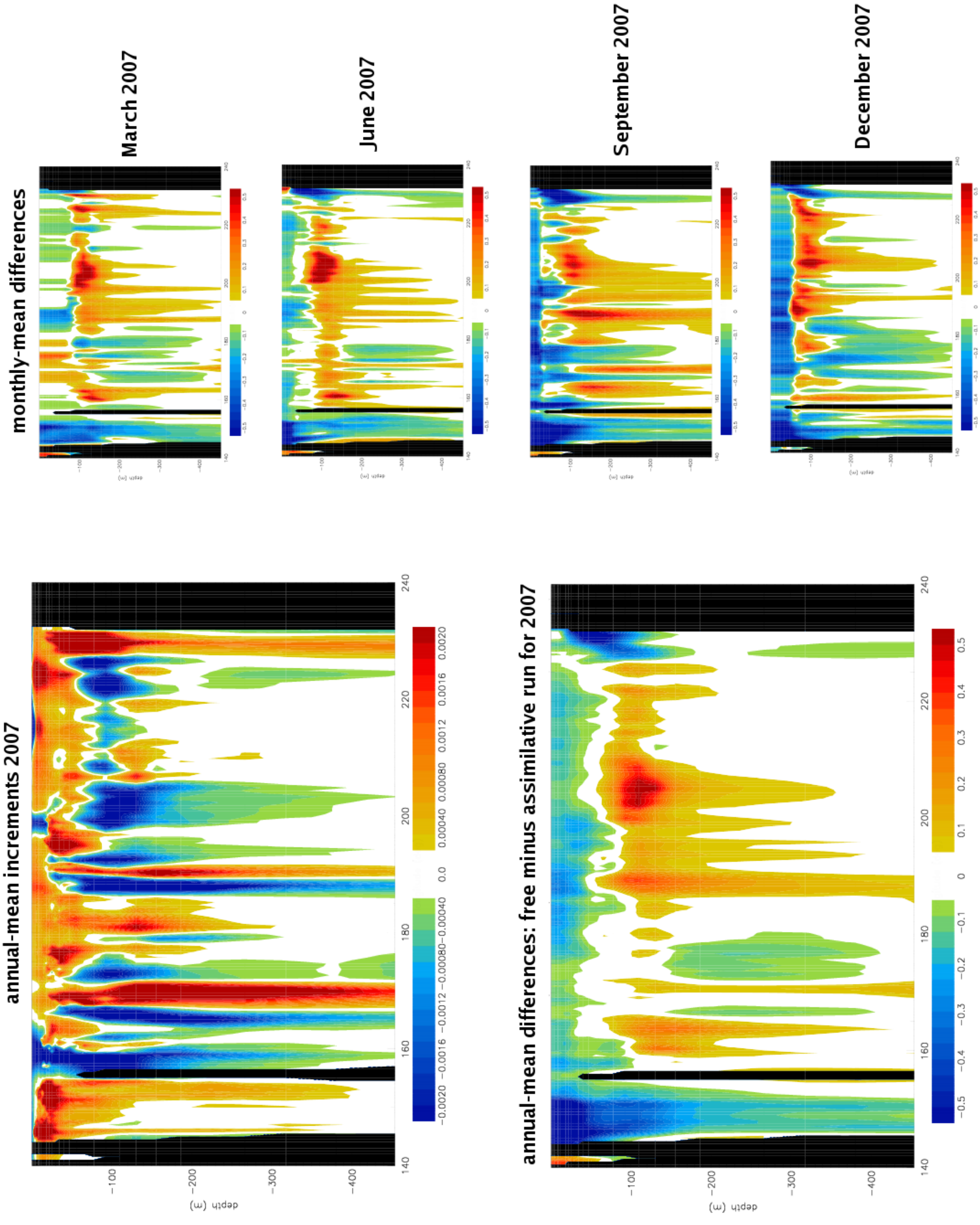

Figure 9: Figure showing cross-sections along 50N in the Pacific of salinity increments (psu/day) and free-minus-assimilative differences (psu). Annual mean plots are shown for the increments and difference fields, and also a timeseries of monthly-mean difference fields, showing the development of the near surface fresh bias.

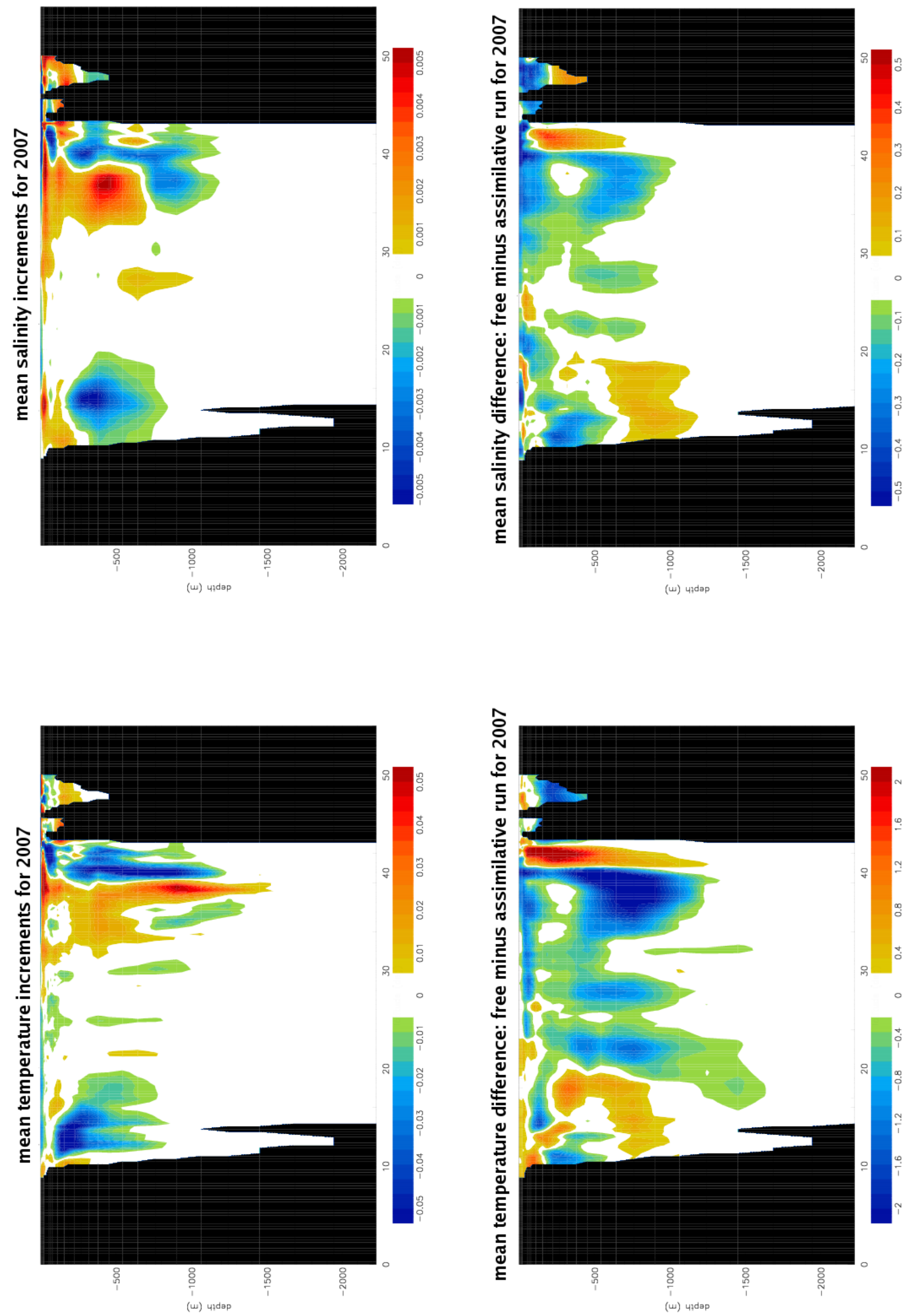

Figure 10: Cross sections along 60W in the North Atlantic. Fields shown are annual mean increments (temperature K/day and salinity psu/day) and free minus assimilative differences (temperature K and salinity psu) from the FOAM V1 hindcast for 2007.

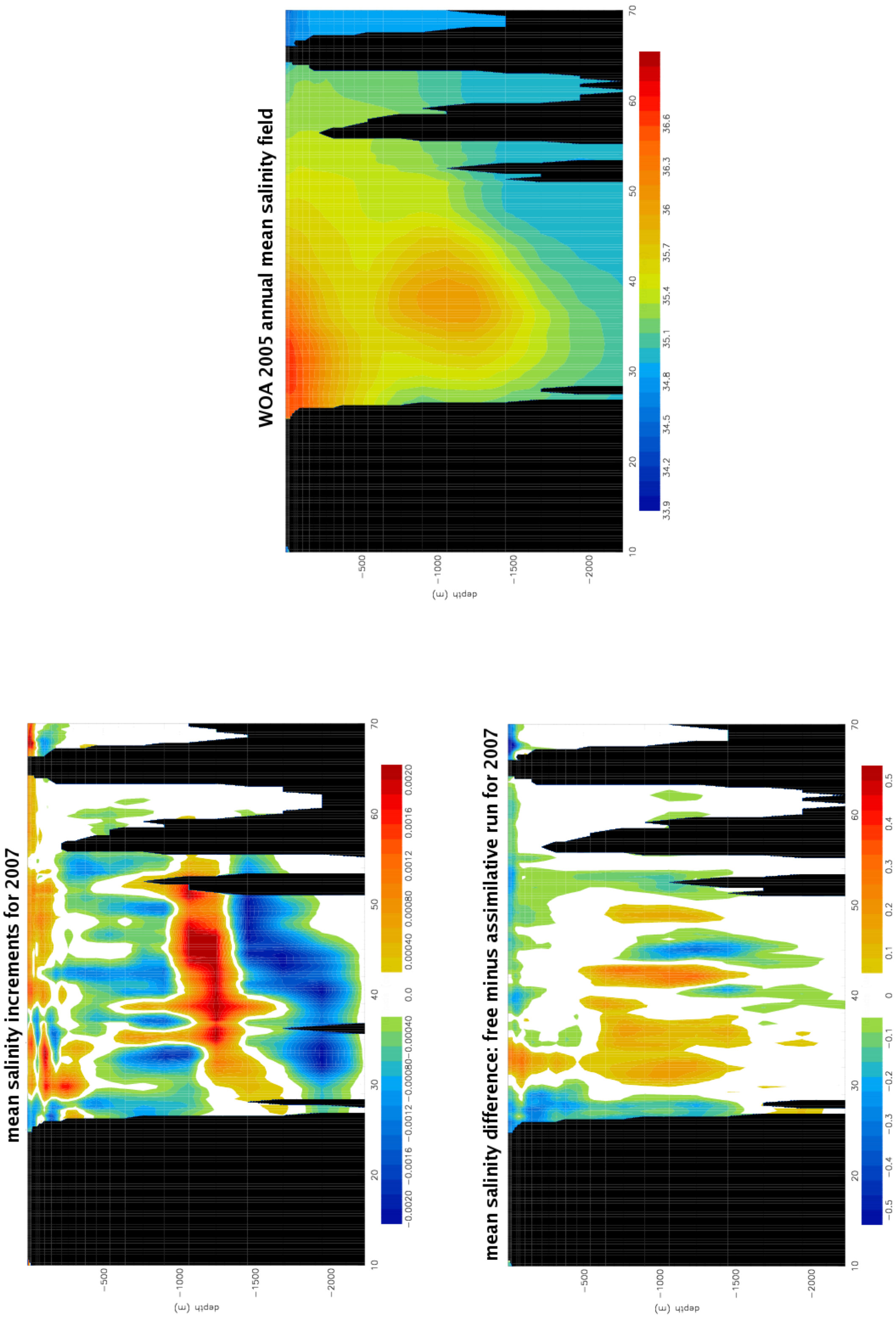

Figure 11: Section along 15W in the North Atlantic, showing annual-mean salinity increments (psu/day, annual-mean salinity differences (psu) between the free and assimilative runs for 2007, and climatological salinity (psu) from the World Ocean Atlas 2005 (Antonov et al 2006).

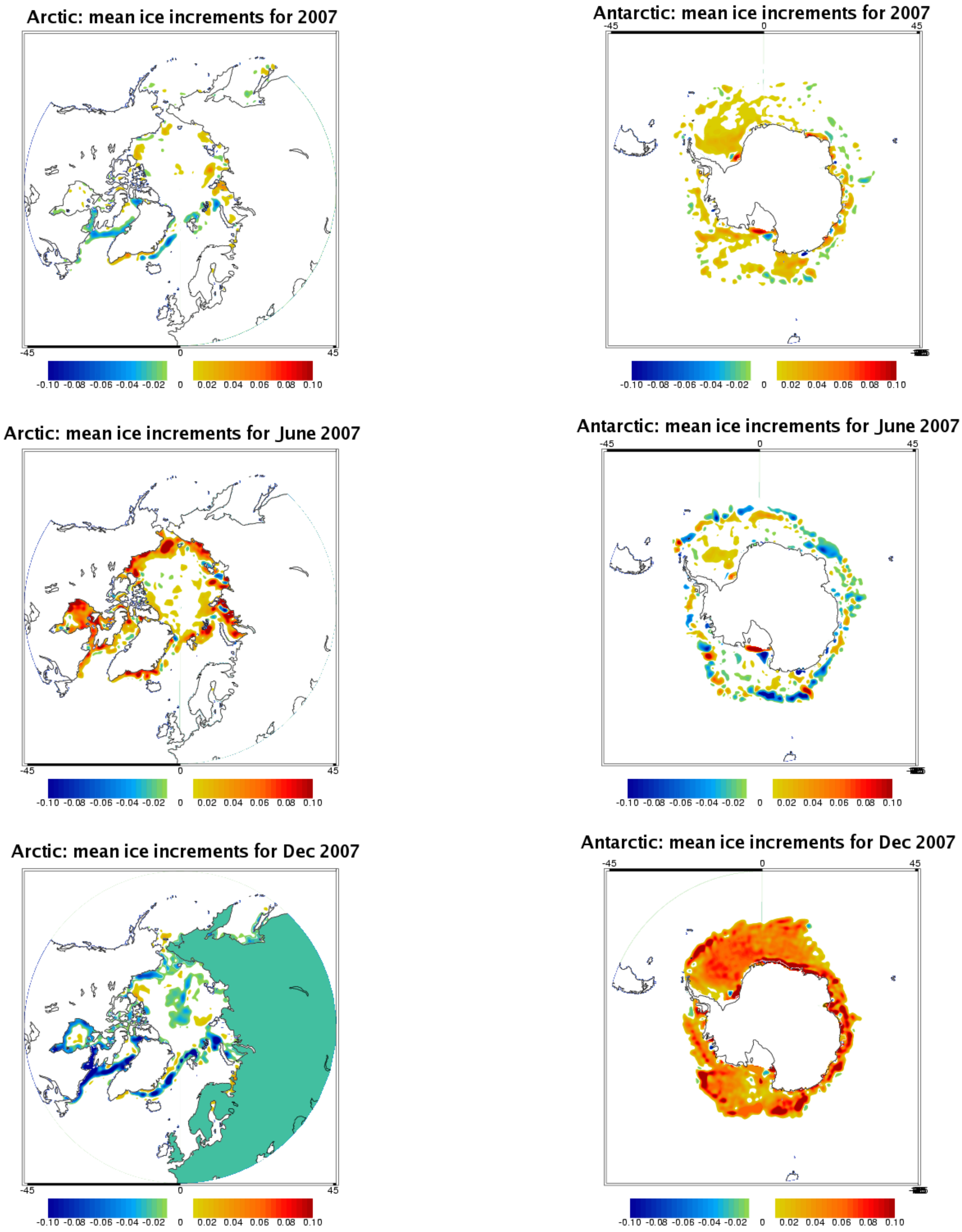

Figure 12: Ice increments (fraction) in Arctic and Antarctic. Annual mean for 2007 and monthly means for June 2007 and December 2007.

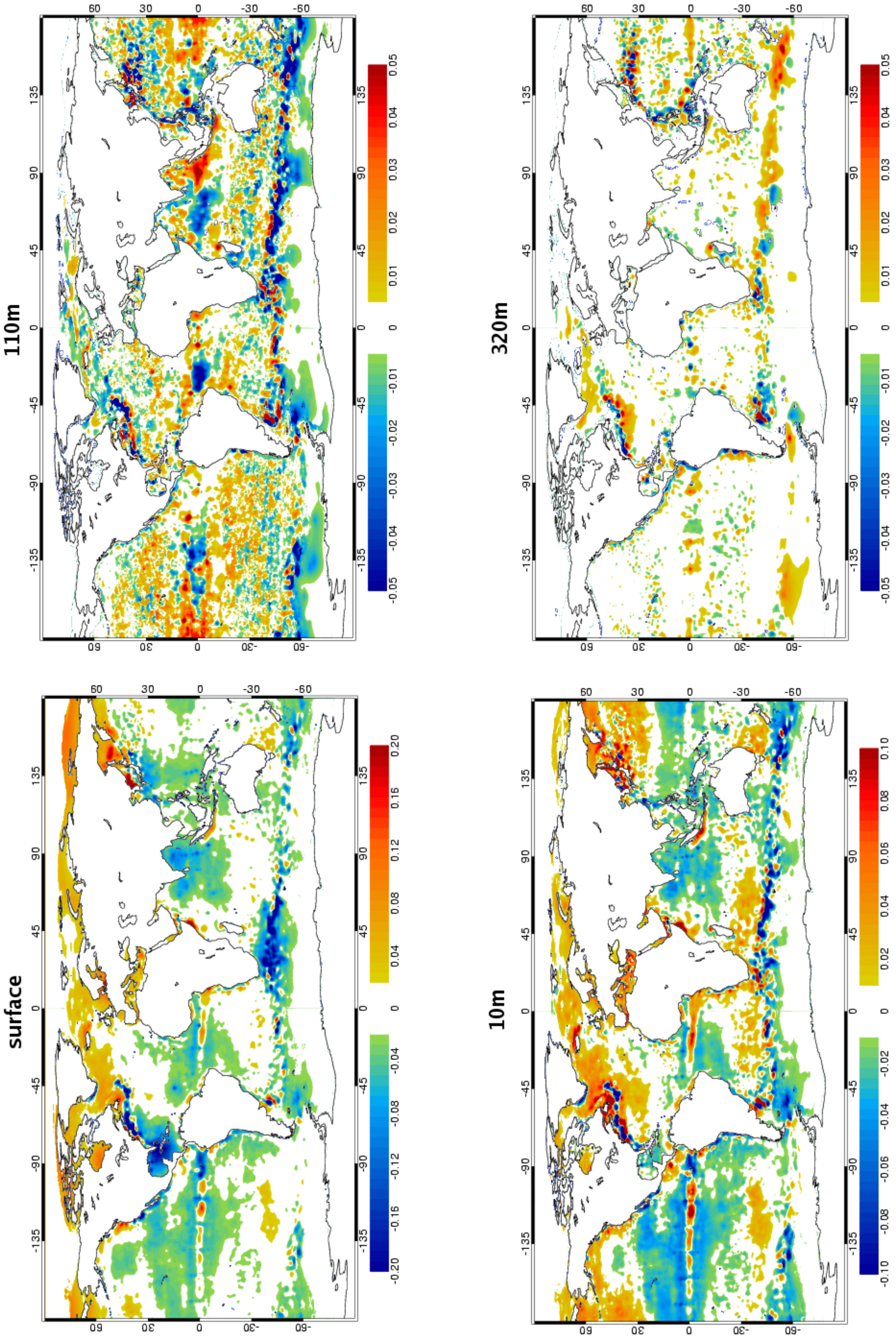

Figure 13: Annual mean temperature increments (K/day) from the FOAM V0 hindcasts for 2007

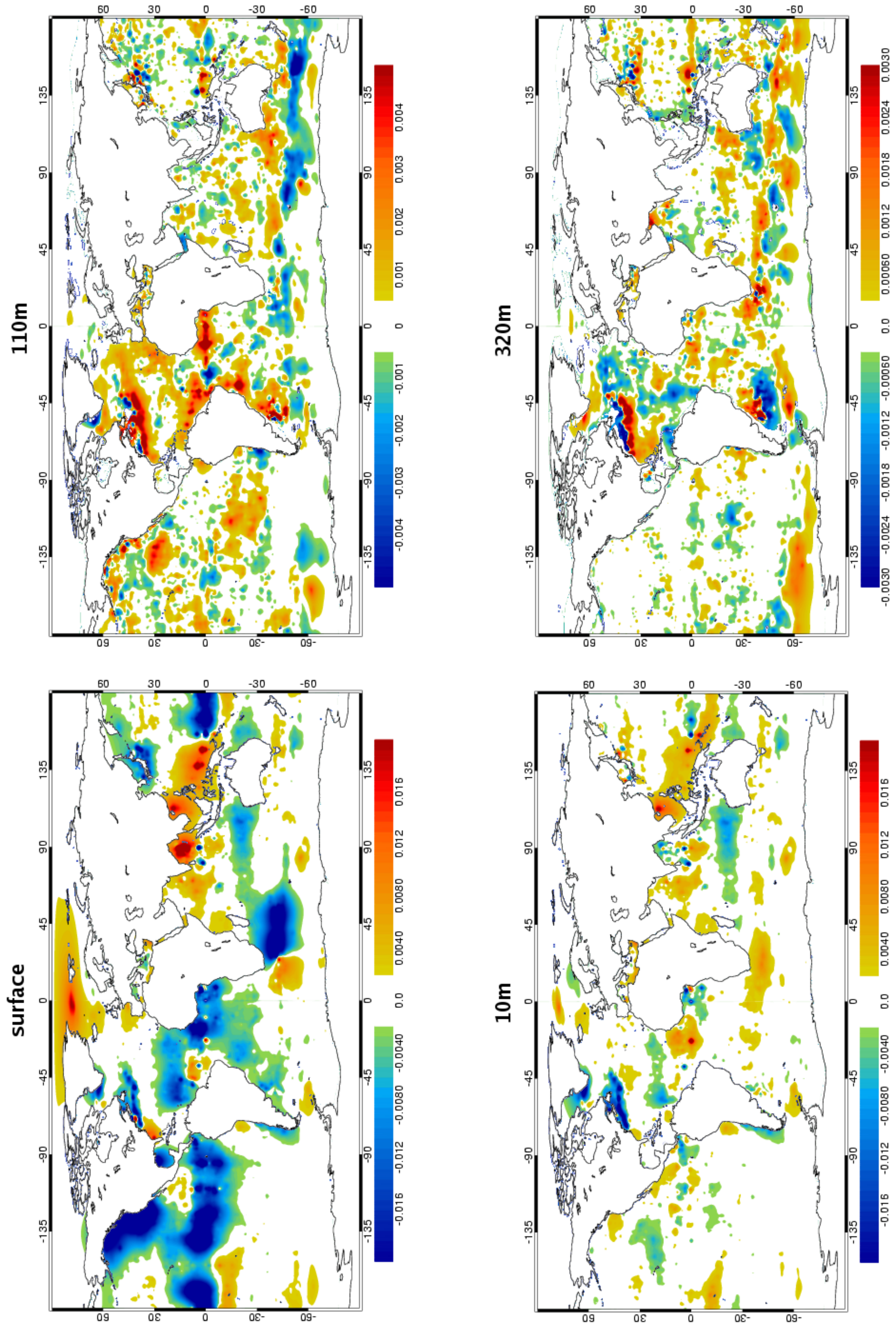

Figure 14: Annual mean salinity increments (psu/day) from the FOAM V0 hindcasts for 2007

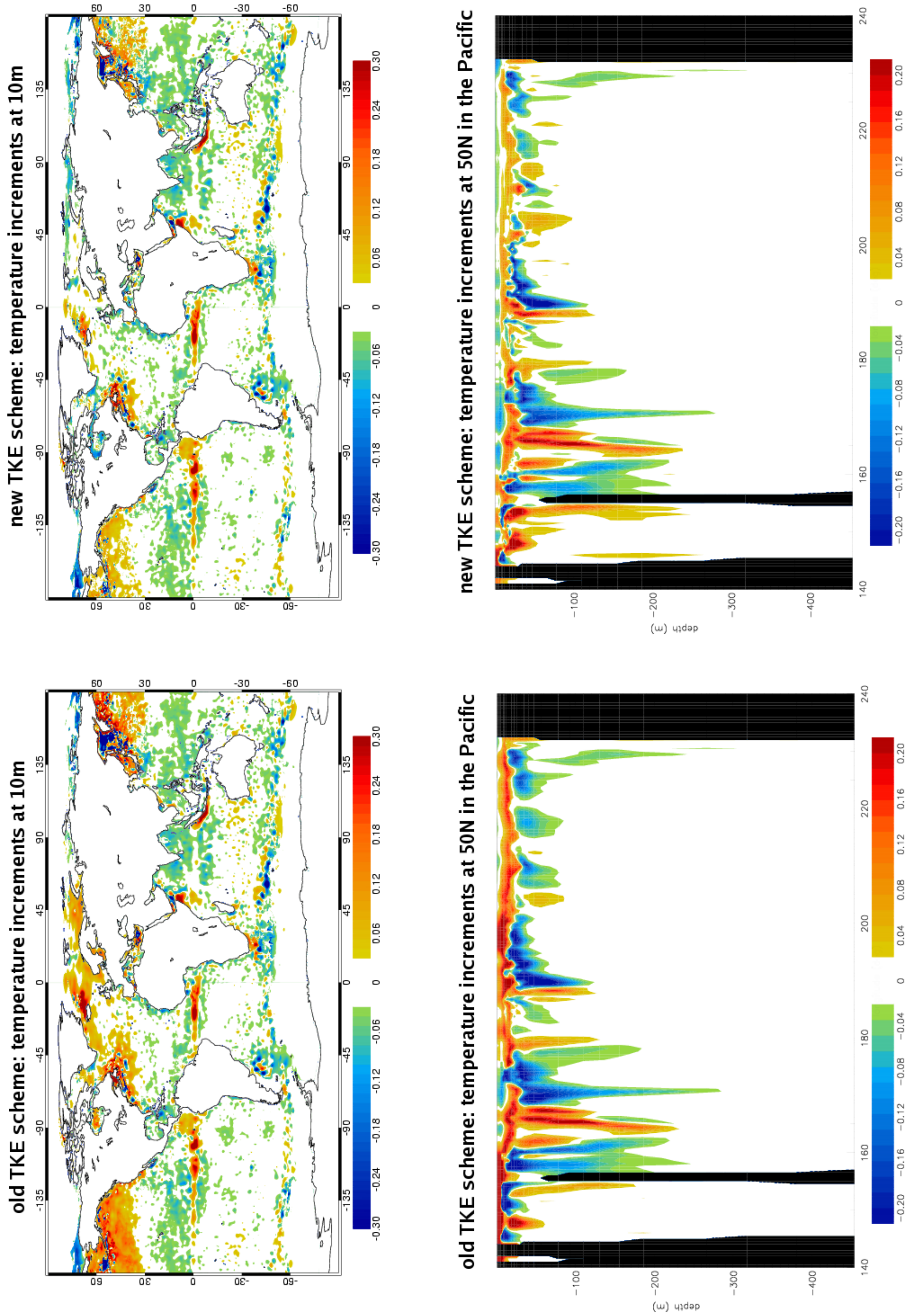

Figure 15: Monthly mean temperature increments (K/day) for August 2007 from sensitivity experiments with the FOAM V1 system, in which the old and new versions of the NEMO TKE scheme were tested. (The new TKE scheme is standard at FOAM V1 and the old TKE scheme was used in FOAM V0). Note that neither experiment included any Haney forcing of the surface heat flux.

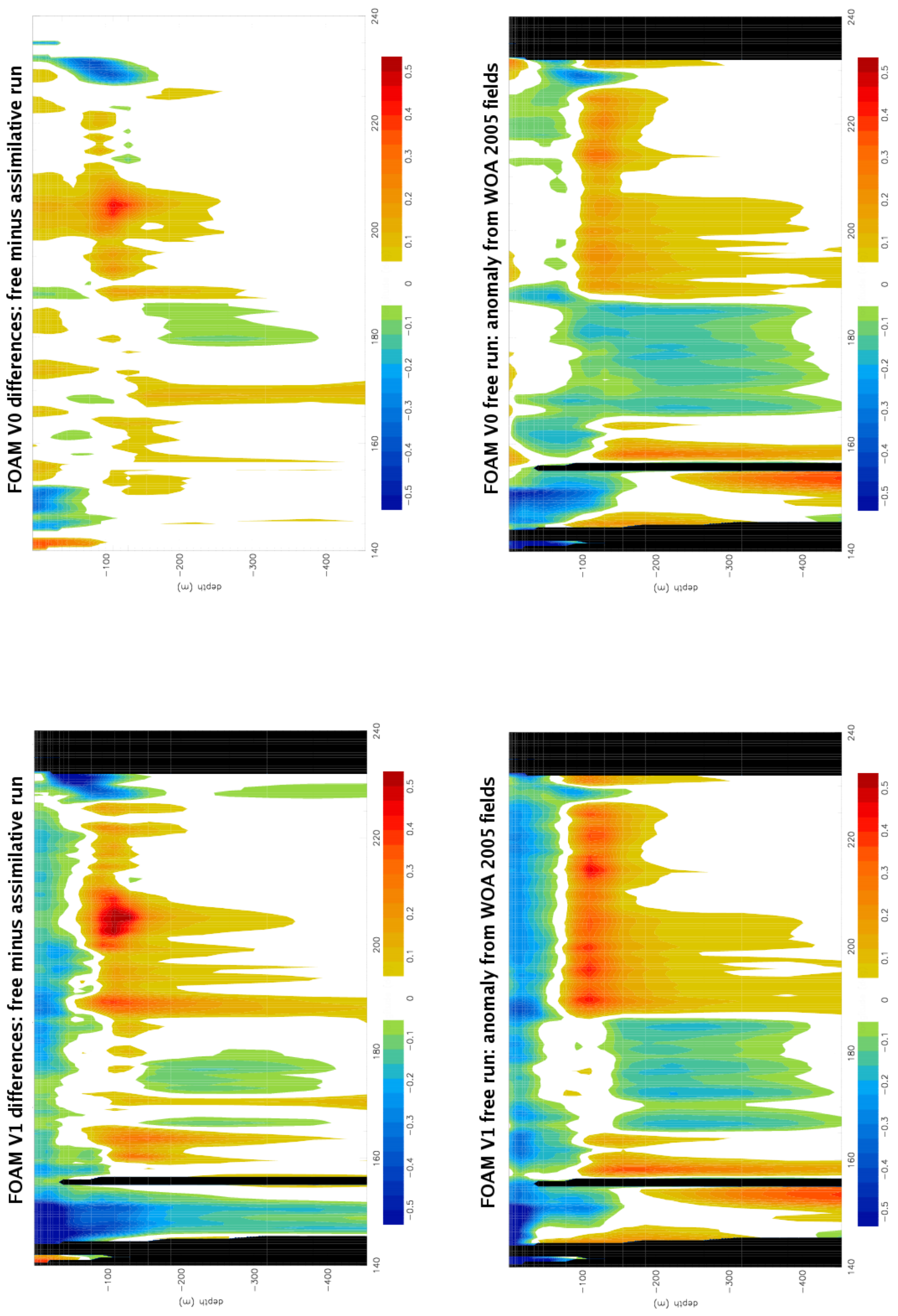

Figure 16: Cross-section along 50N in the Pacific of annual-mean salinity differences (psu) between the free and assimilative hindcast runs for FOAM V1 and FOAM V0, showing the near-surface fresh biases present in V1 but not V0. Also shown are anomaly fields (psu) against the World Ocean Atlas 2005 climatology (Antonov et al 2006) from the free-running hindcasts, which show that the differences are due to model differences between V0 and V1 rather than differences in the assimilation scheme.

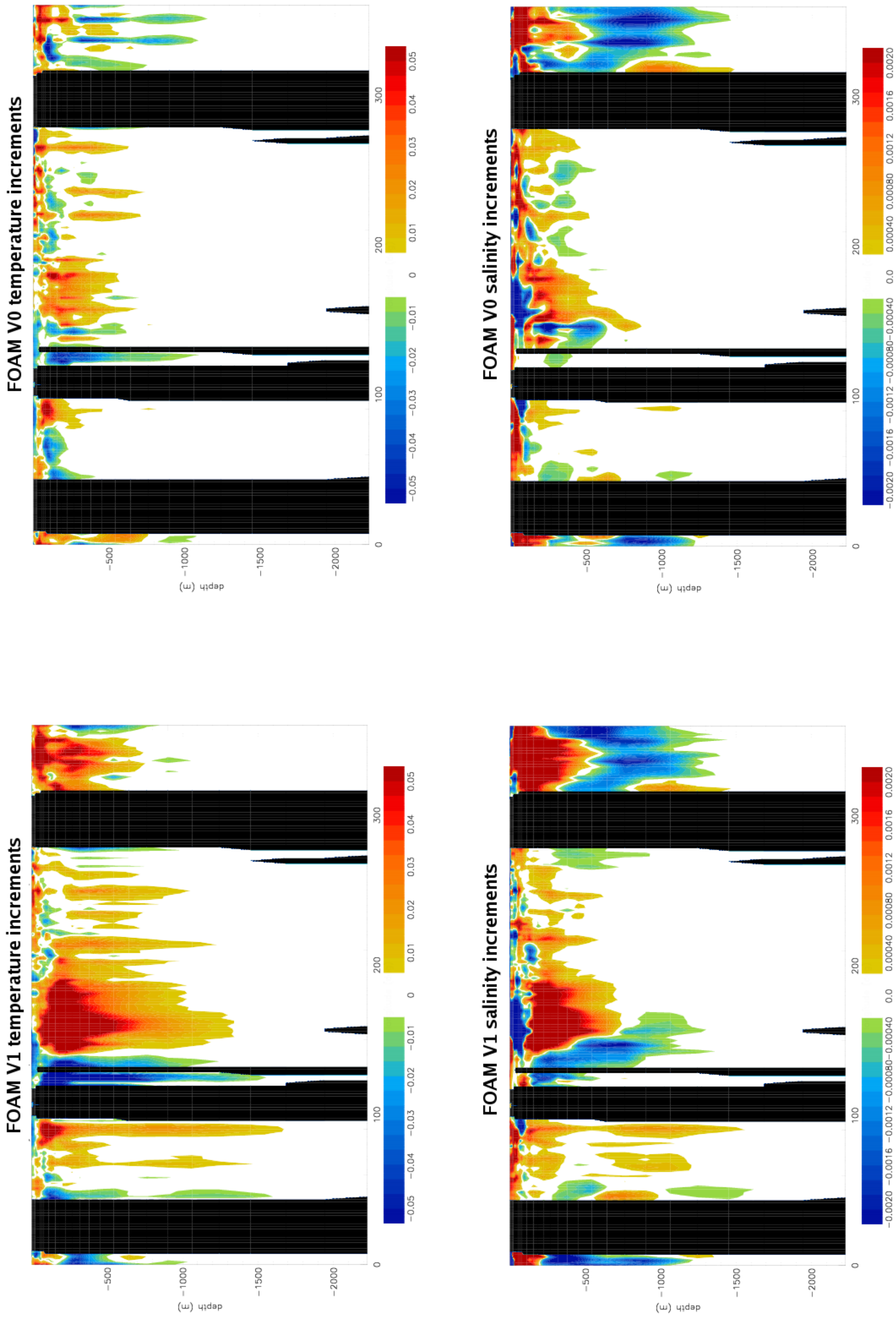

Figure 17: Annual mean temperature and salinity increments (K/day and psu/day): sectional view along the equator. Plots shown for the FOAM Version 1 and FOAM Version 0 systems, illustrating the increased increments between 100m and 500m in FOAM Version 1 compared to FOAM Version 0.

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