To: Dennis McGillicuddy
From: Larry Anderson
Date: July 30, 2008

North Atlantic Report #60:
Maltrud's Simulations with 3 Phyto Groups

1. Fraction of Each Phytoplankton Group

Figs. 1 and 2 show snapshots of Total Chl in the Sargasso, and the fraction that each phytoplankton group (diatoms, diazotrophs, small phytoplankton) contribute. The contribution from DIAZ is always small; consequently the fractions from DIAT and SP generally anticorrelate. Interestingly, in summer both DIAT and SP can cohabitate in equal amounts (Fig. 2a); but blooms are almost always dominated by one group (Fig. 1). The 2-year mean generally captures these distributions (Fig. 3a). DIAT contribute most in the north where winter mixed layers reach the nutricline and Total Chl is high.

Figs. 3b and 4 show bin-averages and 1 standard deviation computed from the 5-day averages over 2 years, 70-35°W and 20-40°N. DIAT and SP chlorophyll generally anticorrelate (Fig. 3b); DIAT correlates well with total Chl, while SP does not (Fig. 4), DIAZ is highest when total Chl (and hence SP and DIAT) are lowest, presumably due to nutrient stress.

- Is there data from the Sargasso that these can be validated against? BATS accessory pigments; process these to equate with DIATCHL, DIAZCHL and SPCHL.
- Also look at relationship between POC flux and phyto type or PP type in the model. Validate this with BATS (or BTM?) data.

2. Cross Sections

Here 9 mid-summer cross-sections are examined, covering various eddy types (Figs. 5-6). The sections (Figs. 7-15) are 5-day averages and show relative vorticity, potential density, vertical velocity, nutrients, sinking POC flux, the three phytoplankton groups, and primary production associated with each group. W is probably significantly time-dependent, and therefore may not be characteristic of longer time means.

Sec. 1 (Fig. 7) passes through a cold core ring, anticyclone and cyclone. W shows strong downwelling at the ring edge. Nitrate and silicate are enhanced in the ring, as is POC flux, but the bloom is SP rather than DIAT. A subsurface max of DIAT exists in the anticyclone, but is not associated with enhanced nutrients or POC flux.

Sec. 2 (Fig. 8) shows an anticyclone and cyclone, which are associated with depressed and lifted nutriclines respectively. Surprisingly, POC flux is greatest in the anticyclone, which is associated with SP (and DIAZ) rather than DIAT.

Sec. 3 (Fig. 9) passes through a weak cyclone and MWE, which doe not show much biological enhancement, and subsurface maximuma in plankton and PP.

Sec. 4 (Fig. 10) shows a cyclone and MWE. Greater POC flux is associated with the MWE, which has enhanced DIAT and DIAZ (and SP-PP).

Sec. 5 (Fig. 11) shows a MWE, anticyclone and cyclone. High upwelling/downwelling is associated with the western edge of the anticyclone. The cyclone shows enhanced nutrients, but the anticyclone has highest POC flux, associated with enhanced DIAT and DIAZ (and SP-PP).

Sec. 6 (Fig. 12) shows a Thinny. Nutrients are depressed, as is POC flux, phytoplankton and PP.

Sec. 7 (Fig. 13) shows a Thinny. Again nutrients are depressed, as is POC flux, phytoplankton and PP.

Sec. 8 (Fig. 14) shows an anticyclone and Thinny. DIAT and DIAZ are enhanced in the anticyclone, but POC flux is highest between the two eddies, seemingly related to high nutrients and PP (by SP and DIAZ).

Sec. 9 (Fig. 15) shows a MWE and cyclone. POC flux is highest in the MWE, in which all 3 phyto groups are enhanced.

In summary, based on these few sections:

i. Thinnies appear associated with low phytoplankton and low POC flux.

ii. The relationship of MWE, cyclones and anticyclones with phytoplankton groups and POC flux is varied. Thus perhaps these relationships are best estimated statistically. DIAZ always make up a small fraction of total Chl, and do not aggregate into POC like DIAT and SP do (at 20% per day), so it is unclear if they make a significant contribution to POC flux. DIAT typically have subsurface maxima in Chl and production, while SP dominate in the surface waters.

- Which cross section is typical for each eddy type, according to the statistics? See next section.
- Is the variability between eddy type, phyto type and POC flux due to time-space lags between production and export? If so, statistical correlations may not be revealing.

3. Phytoplankton Group vs. Relative Vorticity and Latitude

Figs. 16a show vertically-integrated Chl for the 3 phytoplankton groups binned by vorticity and latitude, taken from 5-day averages over 2 years. Panel 5 shows that north of 30°N more intense cyclones are observed than intense anticyclones, which probably has to do being on the south side of the Gulf Stream (viz. cyclonic cold core rings). At 25°N eddies with vorticity > 1e-5 s^{-1} (e.g. dv/dx=(50 cm/s)/(50 km)) are not found. Total Chl (panel 4) primarily shows latitudinal dependence, indiscriminate of vorticity. Note that estimates at the "edges" may not be robust due to low number of observations. In the north, SP and DIAZ are intensified in strong cyclones and anticyclones. Low SP in the south reflects their large-scale distribution (Fig. 1 in Report #57.) DIAT in the north appear to be associated with low vorticity, with a slight preference toward cyclones (contrast with SP). Note DIAT are primarily associated with winter convection that reaches the nitracline (Figs. 1 and 2), which may be indiscriminate of vorticity, though it shouldn't be preferential to low vorticity.

Fig. 16b is the same analysis but for eddies only (Okubo-Weiss parameter < -5e-12 s^{-2}). It shows essentially the same relationships as in Fig. 16a.

Fig. 17a further subsets those eddies with σ_t anomalies at 112 m > 0.01 kg/m^3; thus Mode-Water Eddies are on the left, and standard cyclones (i.e. excluding Thinnies) are on the right. Fig. 17b subsets eddies with $\sigma_t < 0.01$ kg/m^3; thus regular anticyclones (excluding MWE) are on the left, and Thinnies on the right. Highest Total Chl is associated with cyclones (rings?). DIAZ are most enhanced in strong eddies with $\sigma_t < 0.01$. SP are enhanced in strong eddies of all four types. DIAT are most enhanced in regular cyclones with low vorticity (compare with SP).

Figs. 18 and 19 are the same as Figs. 16 and 17 but with the latitude-dependent means subtracted, to better show the anomalies. In Fig. 18b we again see DIAZ associated with strong eddies, though primarily around 35°N. SP are also associted with strong eddies, now also seen in the south. DIAT are generally anticorrelated with SP, being associated with low vorticity, though now we also see an assocation with anticyclones at 30 N. Total Chl is most similar to DIAT.

Fig. 19 again shows Total Chl primarily associated with regular cyclones, DIAZ with strong eddies with $\sigma_t < 0.01$, SP with all eddy types, and DIAT with regular cyclones near 40°N but anticyclones (both regular and MWE) at 30°N.

Given that DIAT respond mostly to winter mixing, which may obscure eddy-driven effects, Figs. 20-23 are a repeat of Figs. 16-19 but using only data from the 6 summer months. Here again we see the same qualitative relationships as in Figs. 16-19, though SP and DIAZ are not as strongly associated with MWE. Summer DIAT are most strongly associated with cyclones (of both kinds) near 40°N and anticyclones (both kinds) at 30°N, and not so much with low vorticity (Fig. 23) as in winter.

- What does it mean that SP are associated with both strong cyclones and strong anticyclones (Fig. 23)? Find example cross sections of this. The former may be Gulf Stream rings (see below).
- DIAZ are most associated with eddies with $\sigma_t < 0.01$, i.e. nitrogen limitation (Fig. 23). Davis and McGillicuddy (2006) saw association with warm salty anticyclones. Examine summer transects at 32○N, to see if they give similar results.
- Why are DIAT associated with low vorticity (all months; Fig. 19) and summer regular anticyclones at 30°N (Fig. 23b), given that isopycnals in regular anticyclones are deepened? Maybe this latter result is not robust due to low number of observations.
- Could the high Chl associated with cyclones just be cold core rings carrying high Chl slope water? I.e. how can tell which of these relationships are due to north-south advection vs. biological response? Generally cyclones propogate to the NW, though cold core rings transport to the south.

Figs. 24-31 similarly bin primary production and sinking POC flux. Figs. 28-31 are for summer only, while Figs. 26-27 and 30-31 have latitudinal means subtracted. Total PP and

POC flux appear to be primarily enhanced by SP in regular cyclones at 35-40°N, and by DIAT in MWE at 30°N.

Movies showing phytoplankton group and POC flux are at:

http://www.whoi.edu/science/AOPE/people/landerson/NATL/vort_phytolog.avi
http://www.whoi.edu/science/AOPE/people/landerson/NATL/vort_phytolog2.avi

Snapshots from summer (Fig. 32) show the phenomenology behind these statistics. Near 40°N high SP and POC flux are associated with positive vorticity on the north side of the Gulf Stream, rather than isolated eddies. As SP decreases farther north, this appears to be a biological response to the Gulf Stream front. At 30-32°N, one finds mostly cyclones associated with low DIAT and POC flux than anticyclones associated with high DIAT and POC flux (though a couple are seen near 42 W and 69 W on day 585). The movie shows that these biomass-poor cyclones come from the east, and did not have a bloom the previous spring.

Figs. 33-39 show cross sections of these features. Day 285 Sections 1 and 2 (Figs. 33 and 34) cut across the high-SP cyclonic side of the Gulf Stream. Nitrate and silicate are elevated, so it is unclear why SP are stimlated instead of DIAT. Day 285 Section 3 (Fig. 32) is identical to Sec. 6 in Figs. 5, 6 and 12, and is a Thinny.

Day 585 Sections 1 and 2 (Figs. 35 and 36) cut across high DIAT anticyclones near 30°N. Sec. 1 is a "MWE", with isopycnals at 112 m raised (though not at 175 m). Sec. 2 is more complex: a regular anticyclone with nutrients raised only in the east half of it, due to either horizontal or vertical advection.

Day 585 Sections 3-5 (Figs. 37-39) show low POC flux cyclones near 30°N. Sections 3 and 4 are Thinnies. Section 5 is more complex: while isopycnals are raised at 175 m, at 100 m they are locally depressed at the center and raised on the edges.

Thus the low POC flux anomalies appear to be associated with Thinnies coming in from the east, which seem to be the dominant type of eddy at this latitude, according to the movie:

http://www.whoi.edu/science/AOPE/people/landerson/NATL/class_5e12.avi

Note by "MWE" and "Thinnies" is meant anticyclones with isopycnals at 112 m diplaced upward, and cyclones with isopycnals at 112 m diplaced downward respectively; no analysis has bee done on Mode Water content.

- Why does the cyclonic side of the Gulf Stream stimulate SP instead of DIAT (Figs. 33, 34)? Silicate is sufficient. Diatoms are elevated in the anticyclonic parts. Maybe production is stimulated in the mixed layer, where SP seems able to outcompete DIAT; then shading inhibits DIAT below. Look at the DIAT-dominated spring bloom, to see if the DIAT are only subsurface.

- What in the biological model allows DIAT vs. SP to dominate? SP have lower nutrient half-saturations (Table 1 in Report #57), so they should dominate where nutrient-limited (surface layers); DIAT have a higher maximum Chl/N ratio, which might (must) help them dominate in the DCM. Are these the right mechanisms? (Actually DIAT can convert intracellular NO_3 to NH_4 in the light and dark, while SP can only convert it in the light, so perhaps DIAT should have a lower kNO3, or a light-dependent formula used.)

- Look at the whole basin, to see where the Thinnies at 30°N come from. They do not appear to be locally generated, or regular cyclones converting into Thinnies (at least west of 35°W). So are they a different water mass (T-S)? Then their low POC flux may not be a biological response so much as an advective redistribution of oligotrophic water. Are Thinnies observed at BATS i.e. low POC flux correlated with $\sigma < 0.01$?

- In the biological model, the terms that contribute to POC flux are DIAT and SP aggregation (both 20% of standing stock per day), DIAT and SP mortality (0.5% and <4% per day respectively) and a contribution from zooplankton. This is why DIAT and SP contribute about equally to POC flux. But should they?

- Do these cross sections agree with field observations e.g. EDDIES? Compute model and observed statistics at BATS of POC flux vs. other properties (SLA, σ anomaly at 100 m; PP and Phyto type.

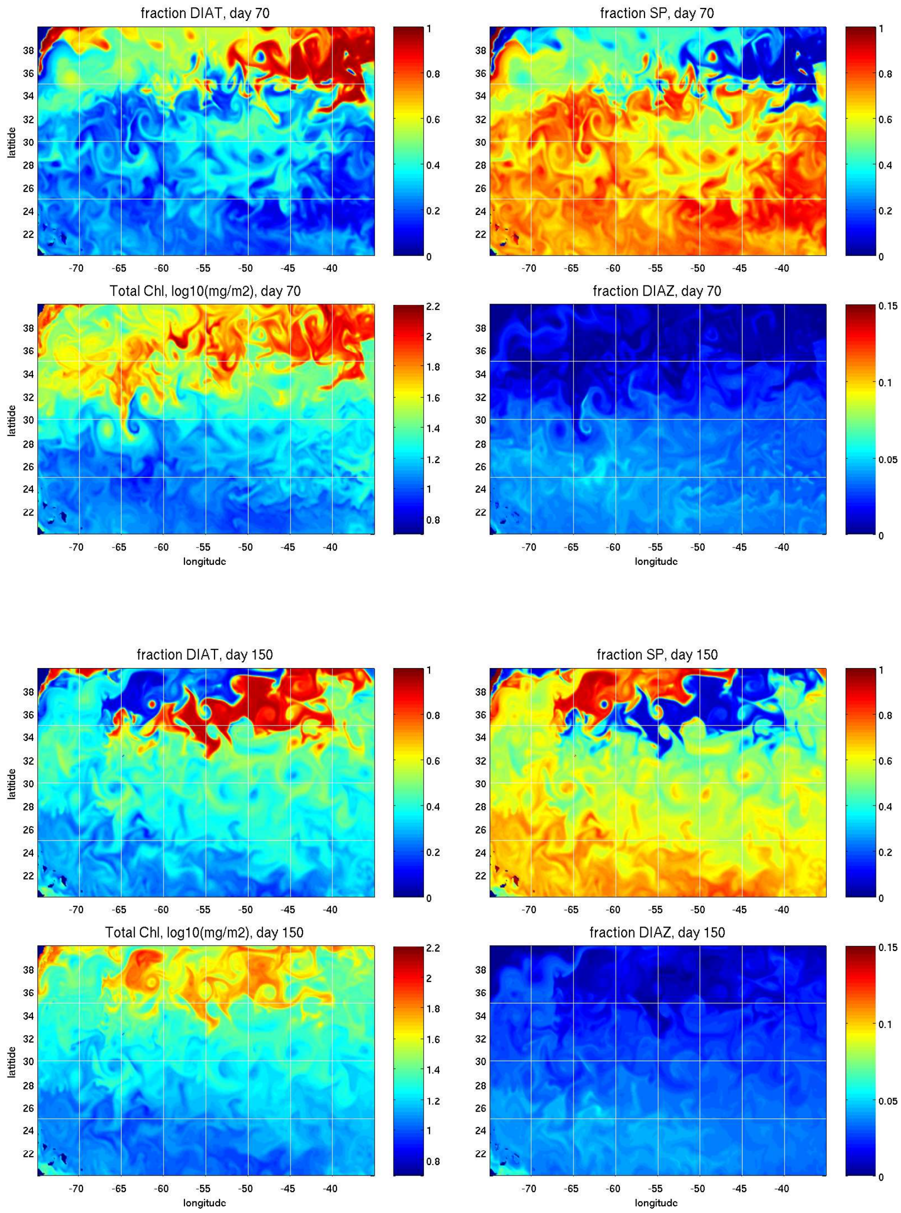


Fig. 1. (a) day 70, (b) day 150.

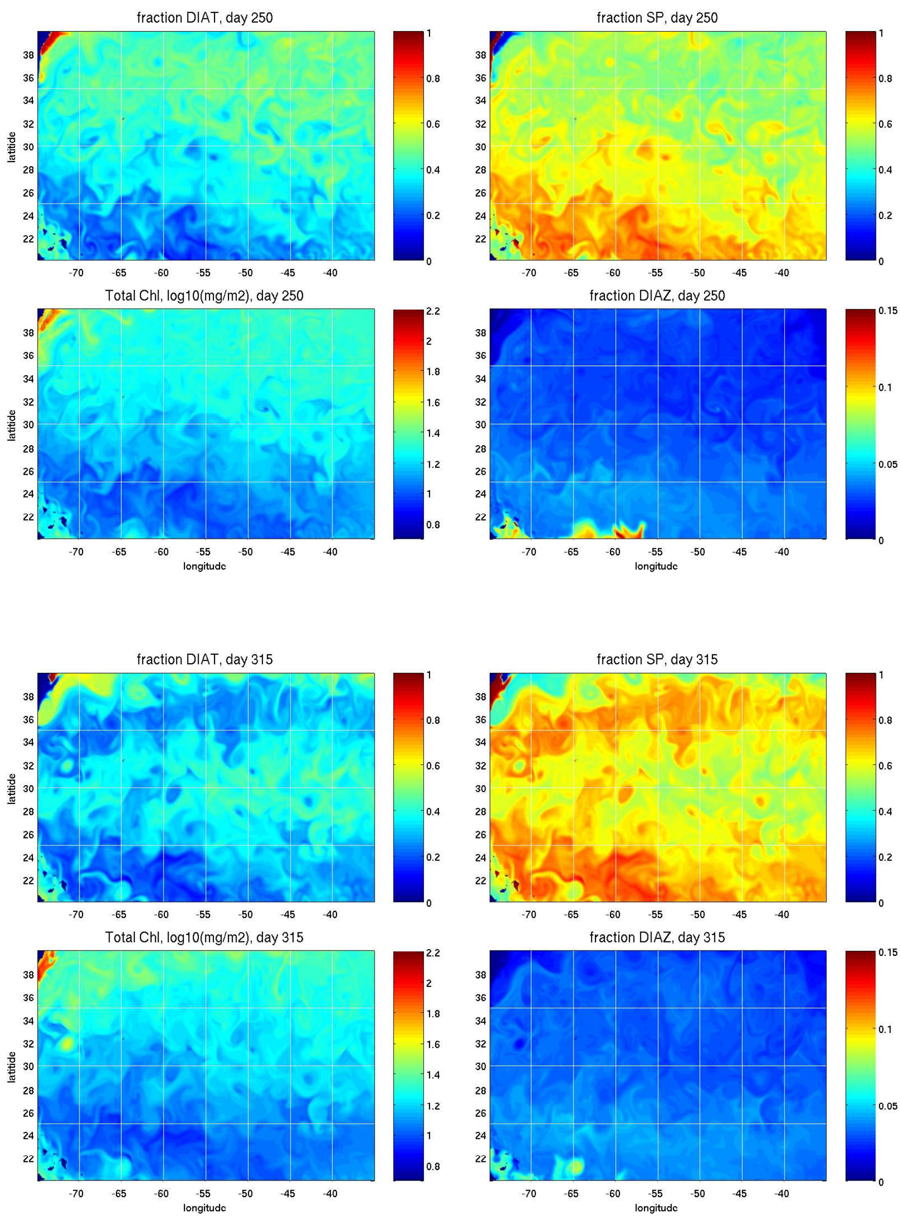


Fig. 2. (a) day 250, (b) day 315.

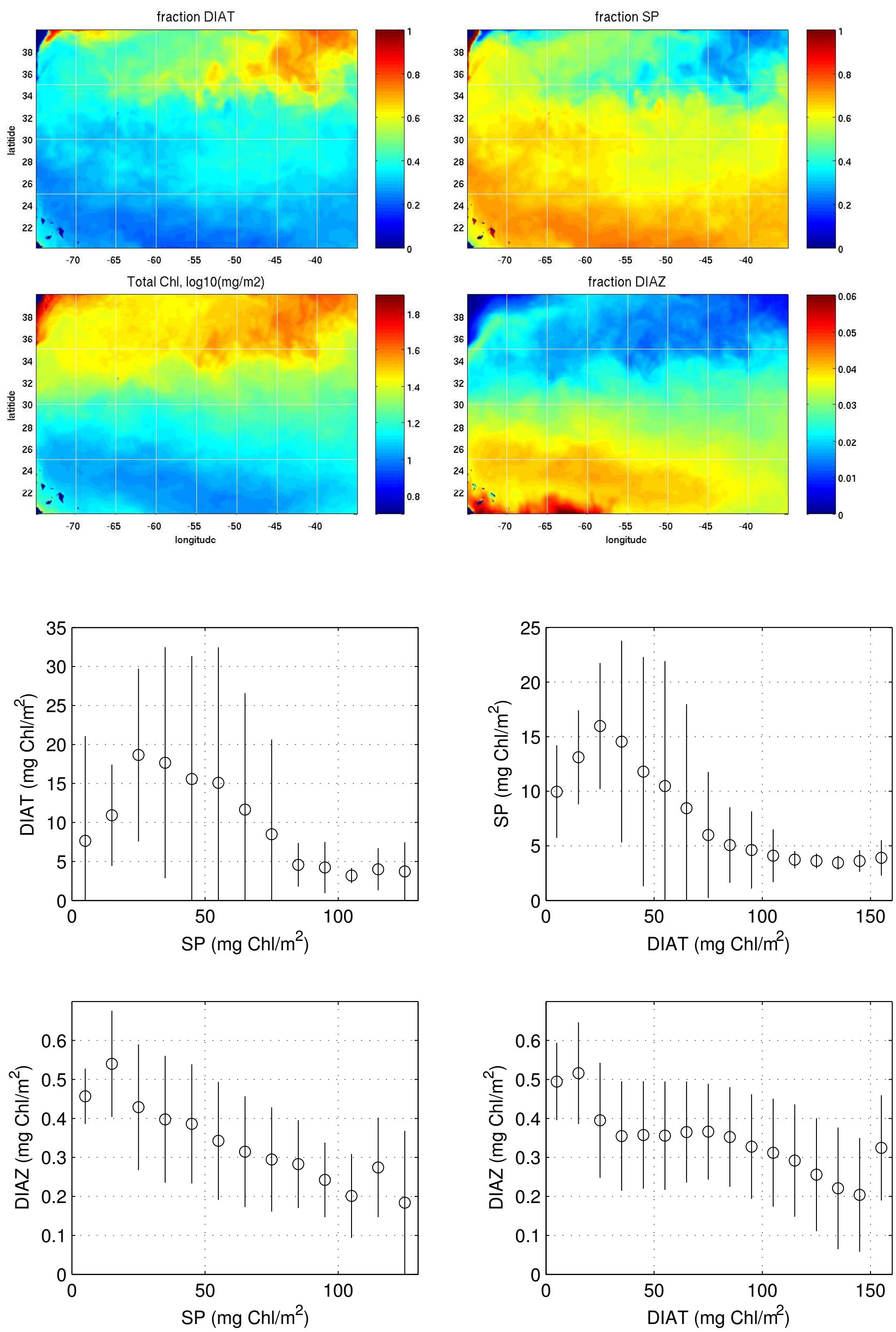


Fig. 3. (a) 2-year mean, (b) bars are one standard deviation.

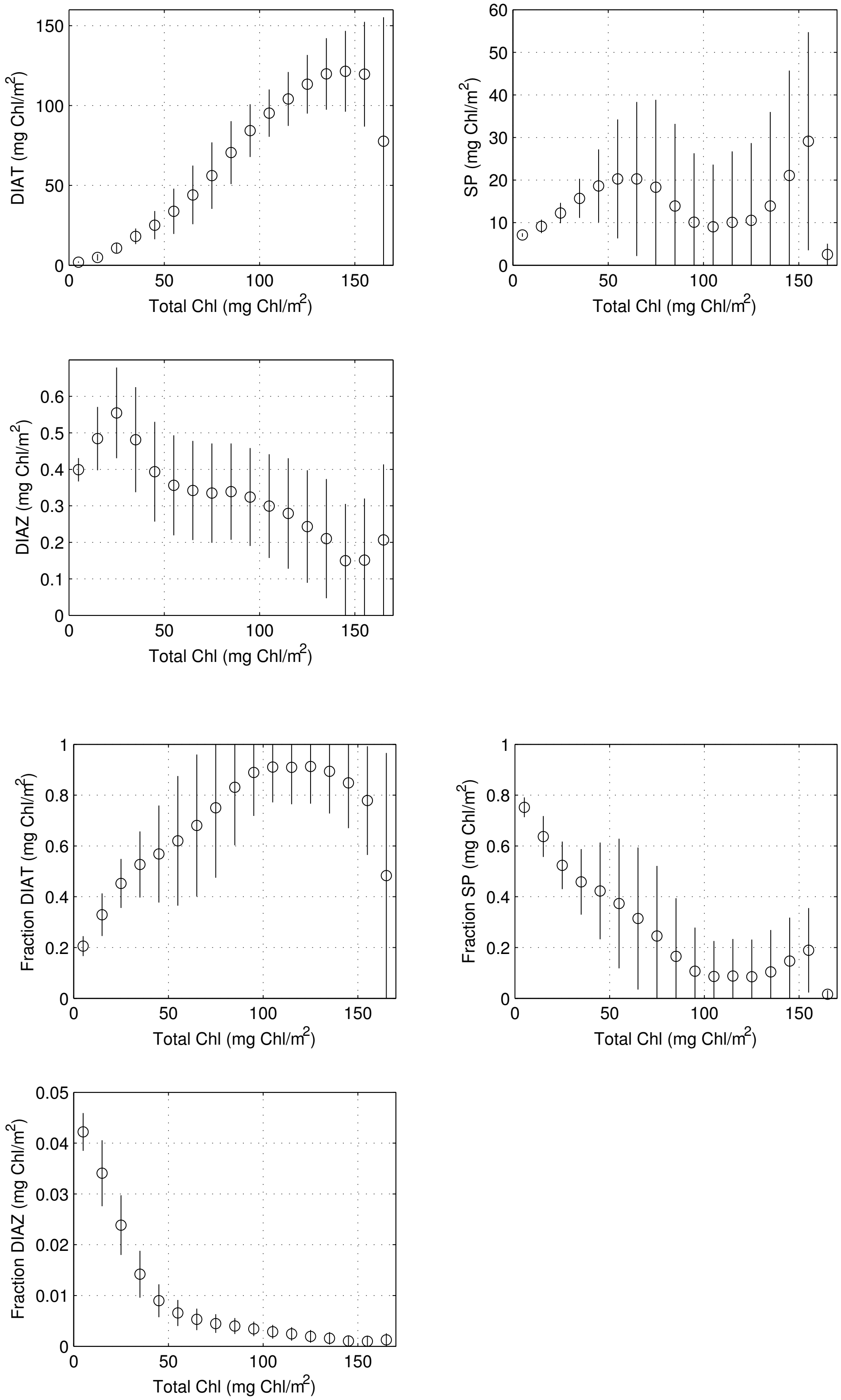
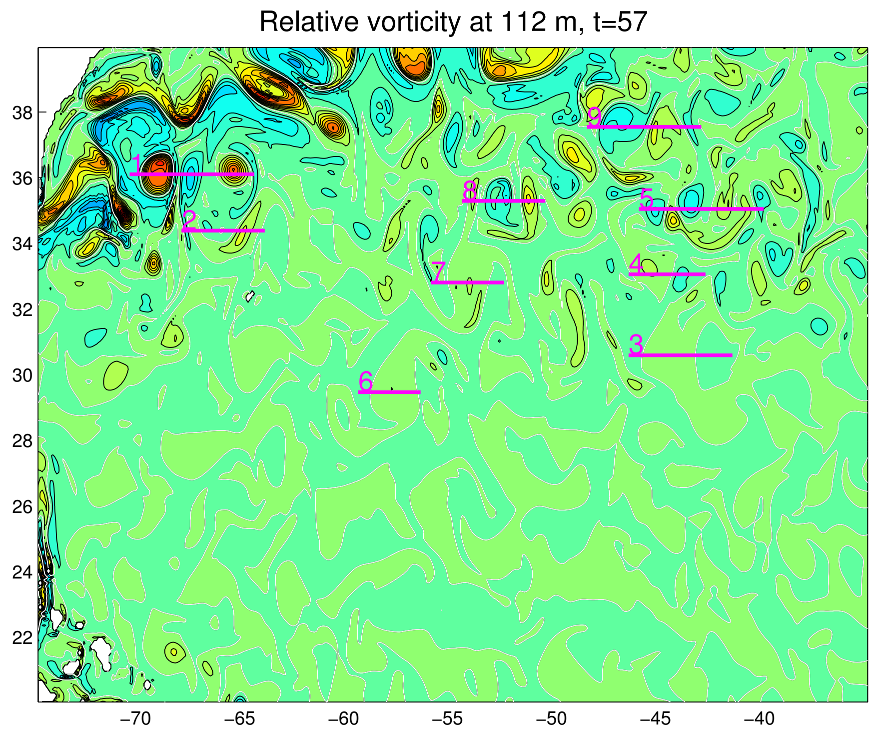
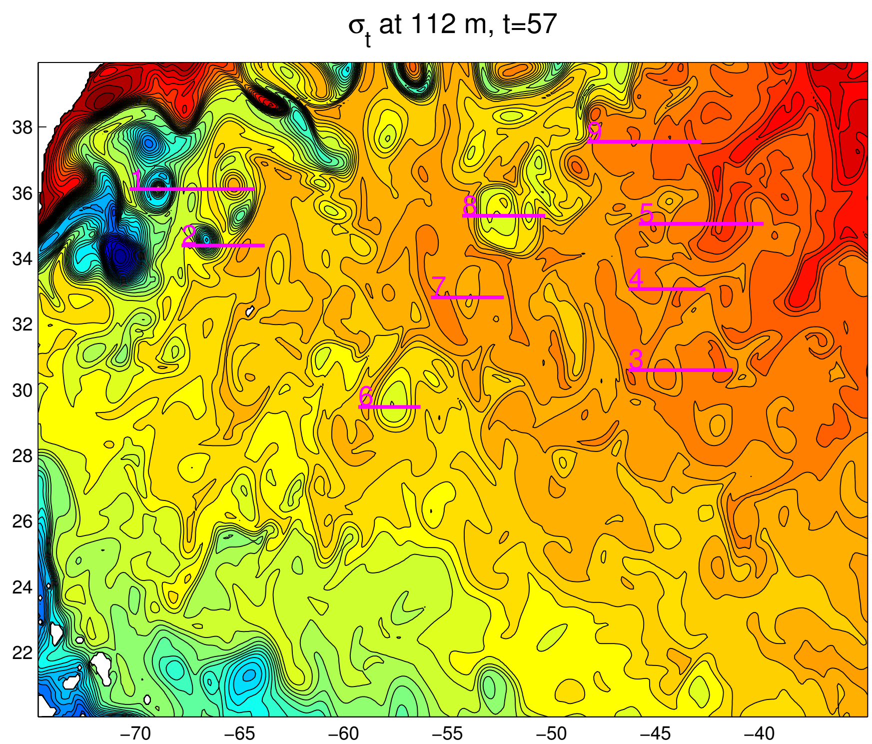


Fig. 4. bars are one standard deviation.



Relative vorticity at 112 m, t=57
38
36
34
32
30
28
26
24
22
−70
−65
−60
−55
−50
−45
−40
1
2
3
4
5
6
7
8
9



σ_t at 112 m, t=57
38
36
34
32
30
28
26
24
22
−70
−65
−60
−55
−50
−45
−40
1
2
3
4
5
6
7
8
9

Fig. 5. Day 285.

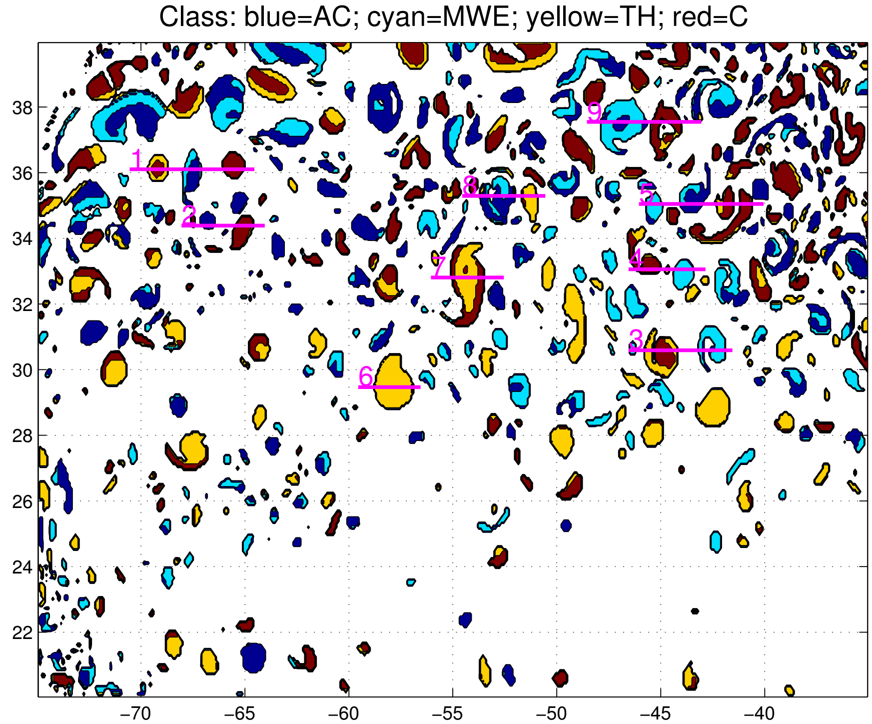
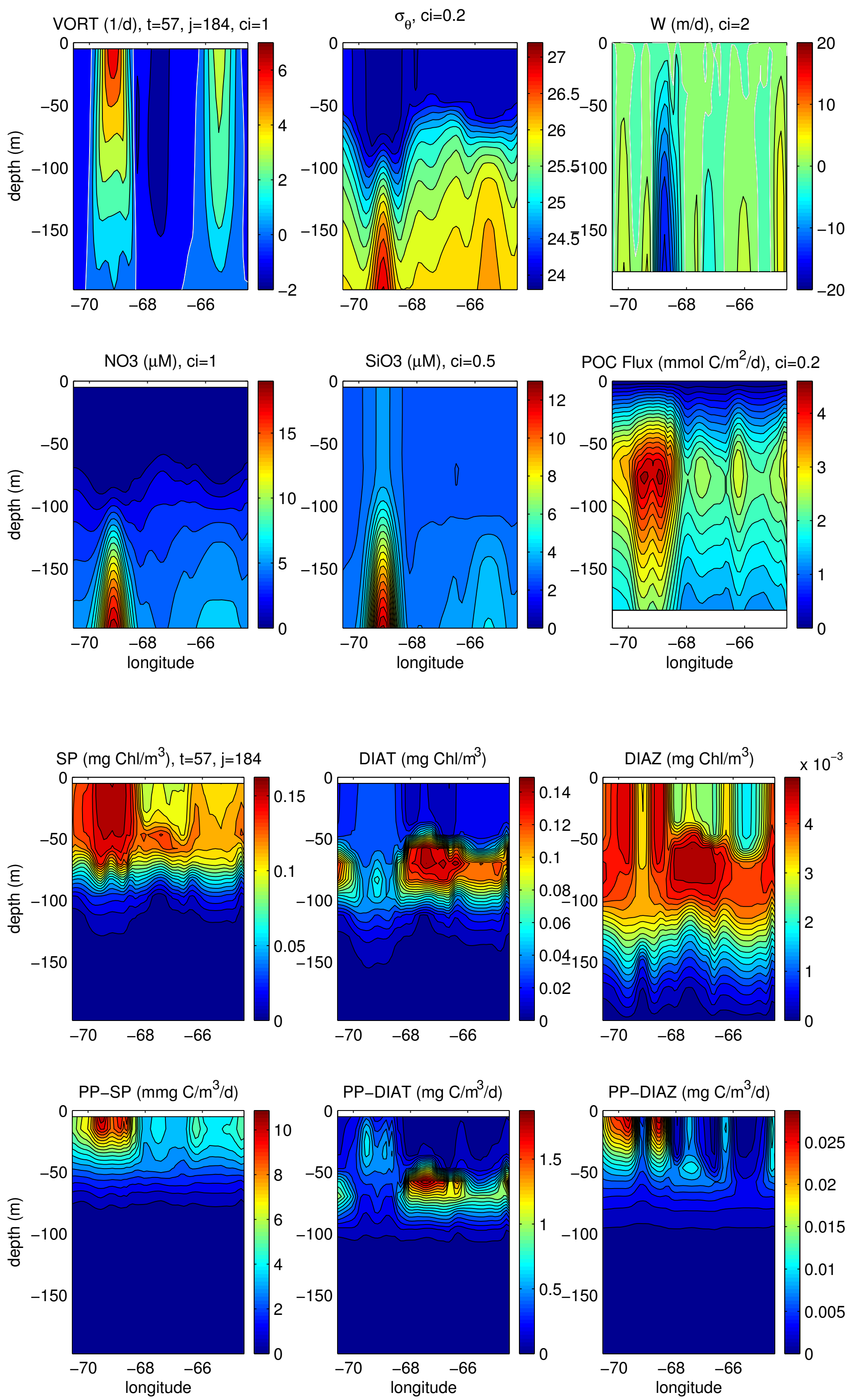

Class: blue=AC; cyan=MWE; yellow=TH; red=C
38
36
34
32
30
28
26
24
22
−70
−65
−60
−55
−50
−45
−40
1
2
3
4
5
6
7
8
9

Fig. 6. Day 285.



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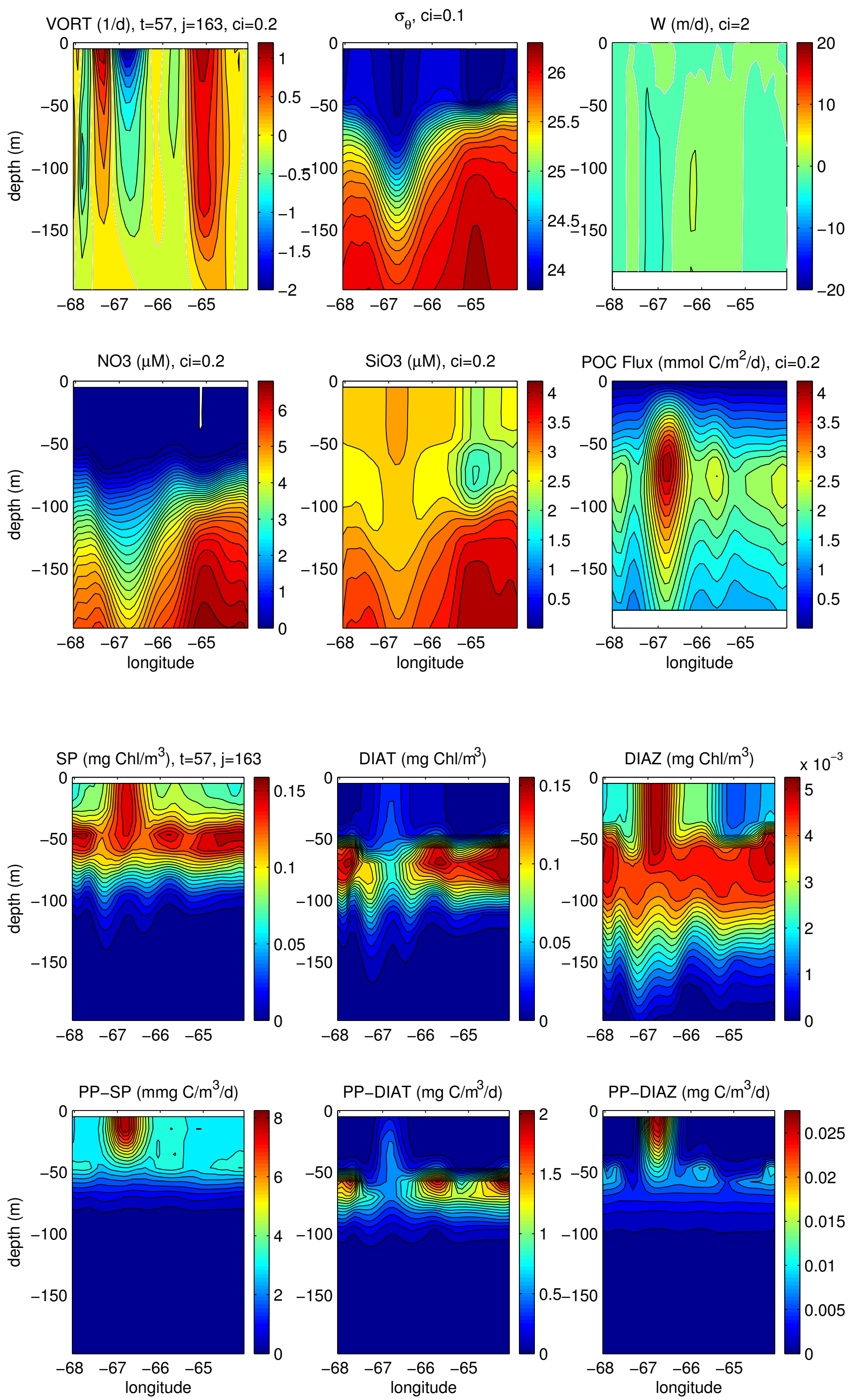
σθ, ci=0.2
W (m/d), ci=2
NO3 (μM), ci=1
SiO3 (μM), ci=0.5
POC Flux (mmol C/m2/d), ci=0.2
SP (mg Chl/m3), t=57, j=184
DIAT (mg Chl/m3)
DIAZ (mg Chl/m3)
x 10−3
PP−SP (mmg C/m3/d)
PP−DIAT (mg C/m3/d)
PP−DIAZ (mg C/m3/d)
depth (m)
longitude

Fig. 7 Sec. 1.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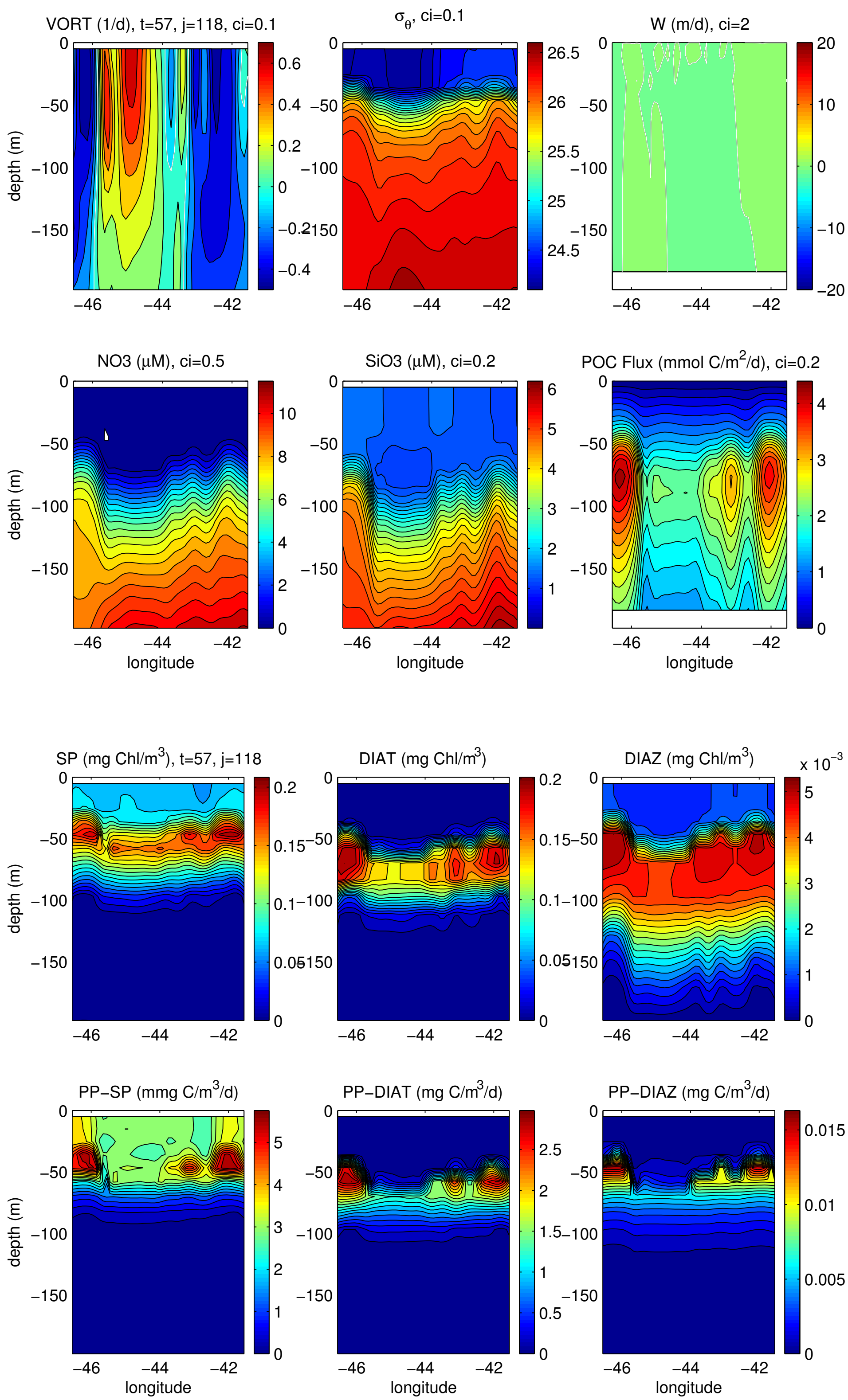
NO3 (μM), ci=0.2
SiO3 (μM), ci=0.2
POC Flux (mmol C/m^2/d), ci=0.2
SP (mg Chl/m^3), t=57, j=163
DIAT (mg Chl/m^3)
DIAZ (mg Chl/m^3)
x 10^{-3}
PP−SP (mmg C/m^3/d)
PP−DIAT (mg C/m^3/d)
PP−DIAZ (mg C/m^3/d)
depth (m)
longitude

Fig. 8. Sec. 2.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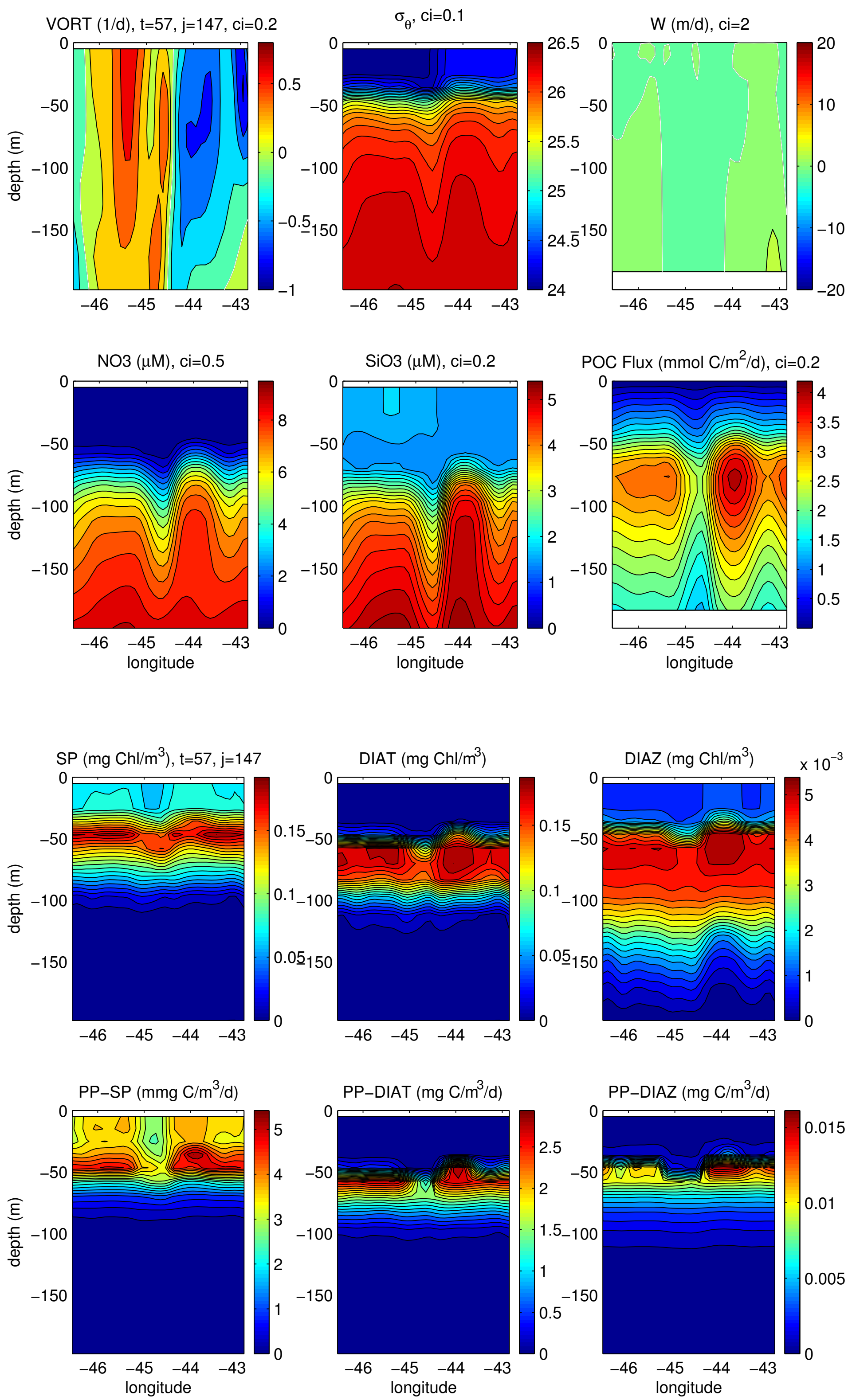
POC Flux (mmol C/m2/d), ci=0.2
SP (mg Chl/m3), t=57, j=118
DIAT (mg Chl/m3)
DIAZ (mg Chl/m3)
x 10−3
PP−SP (mmg C/m3/d)
PP−DIAT (mg C/m3/d)
PP−DIAZ (mg C/m3/d)
depth (m)
longitude

Fig. 9. Sec. 3.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σθ, ci=0.1
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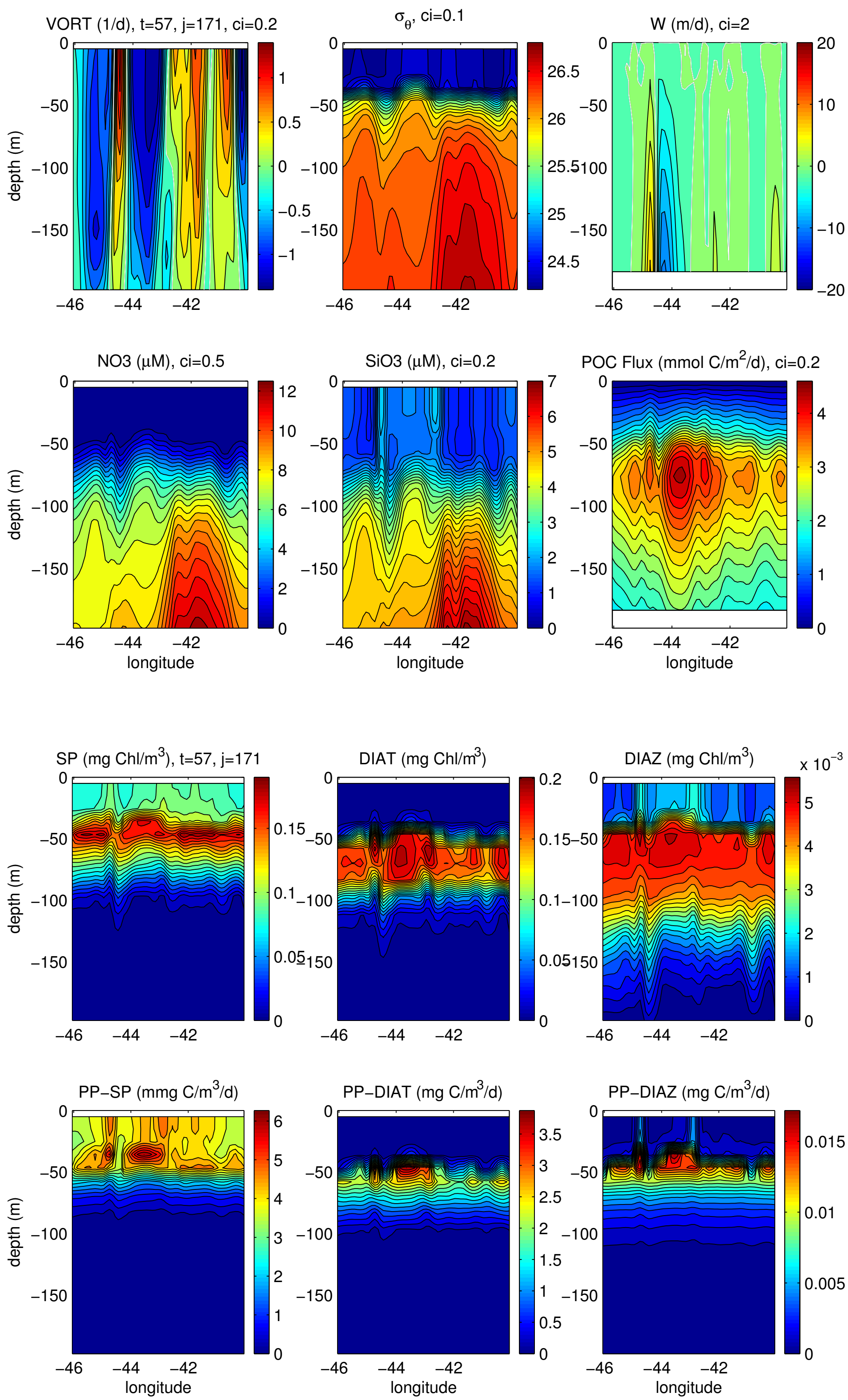
NO3 (μM), ci=0.5
SiO3 (μM), ci=0.2
POC Flux (mmol C/m2/d), ci=0.2
SP (mg Chl/m3), t=57, j=147
DIAT (mg Chl/m3)
DIAZ (mg Chl/m3)
x 10−3
PP−SP (mmg C/m3/d)
PP−DIAT (mg C/m3/d)
PP−DIAZ (mg C/m3/d)
depth (m)
longitude

Fig. 10. Sec. 4.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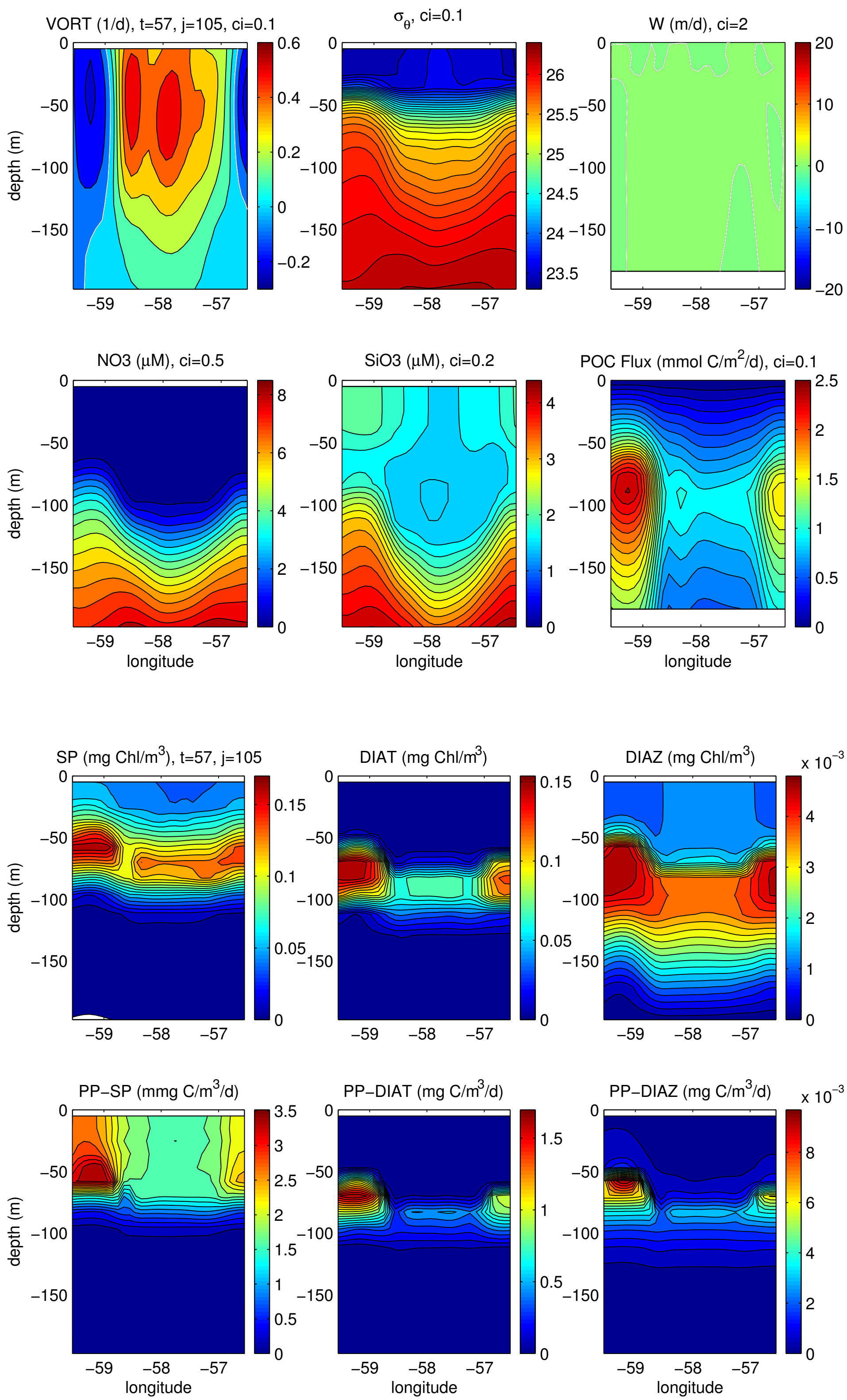
SiO3 (μM), ci=0.2
POC Flux (mmol C/m2/d), ci=0.2
SP (mg Chl/m3), t=57, j=171
DIAT (mg Chl/m3)
DIAZ (mg Chl/m3)
x 10−3
PP−SP (mmg C/m3/d)
PP−DIAT (mg C/m3/d)
PP−DIAZ (mg C/m3/d)
depth (m)
longitude

Fig. 11. Sec. 5.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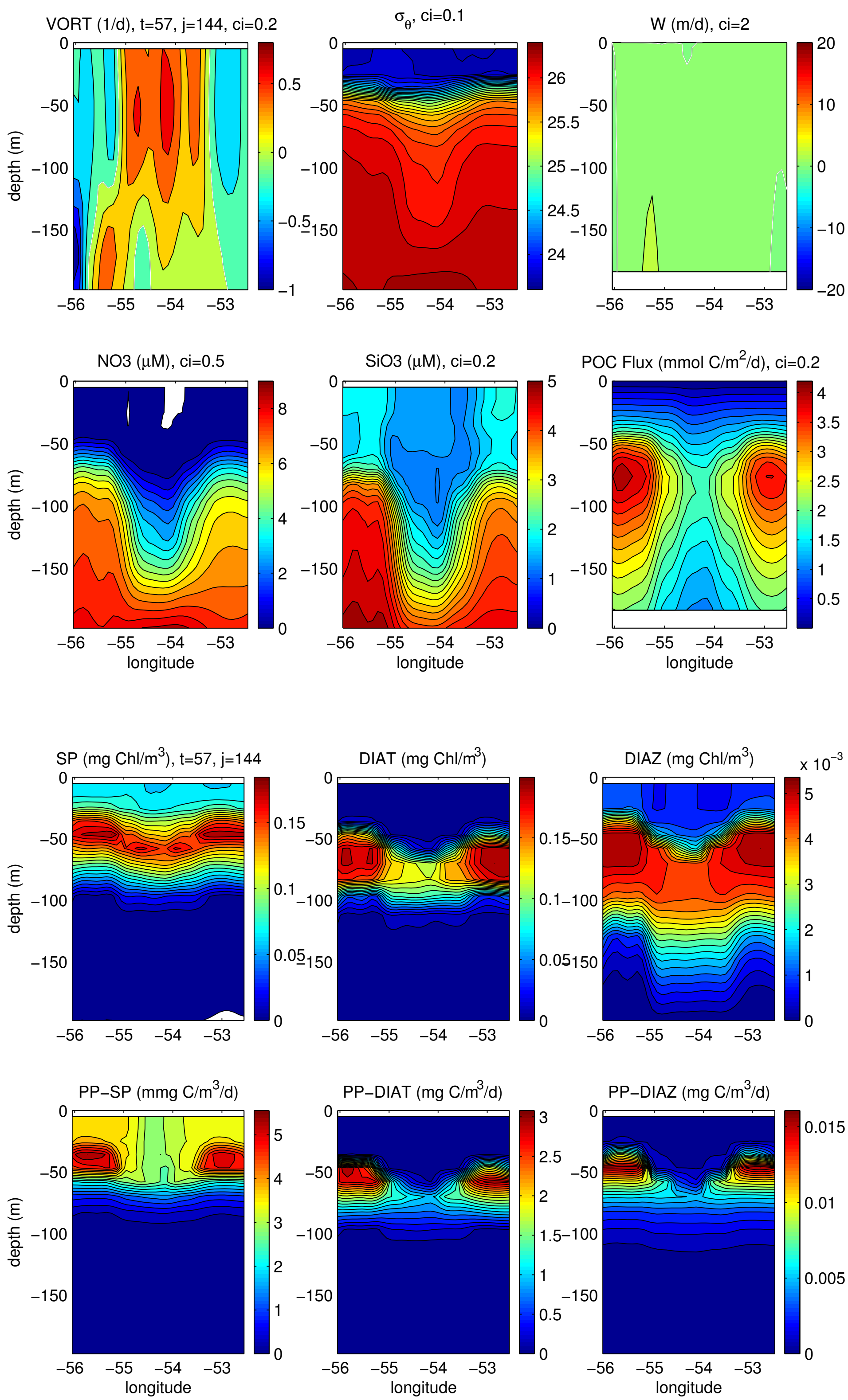
POC Flux (mmol C/m2/d), ci=0.1
SP (mg Chl/m3), t=57, j=105
DIAT (mg Chl/m3)
DIAZ (mg Chl/m3)
PP−SP (mmg C/m3/d)
PP−DIAT (mg C/m3/d)
PP−DIAZ (mg C/m3/d)
x 10−3
depth (m)
longitude

Fig. 12. Sec. 6.



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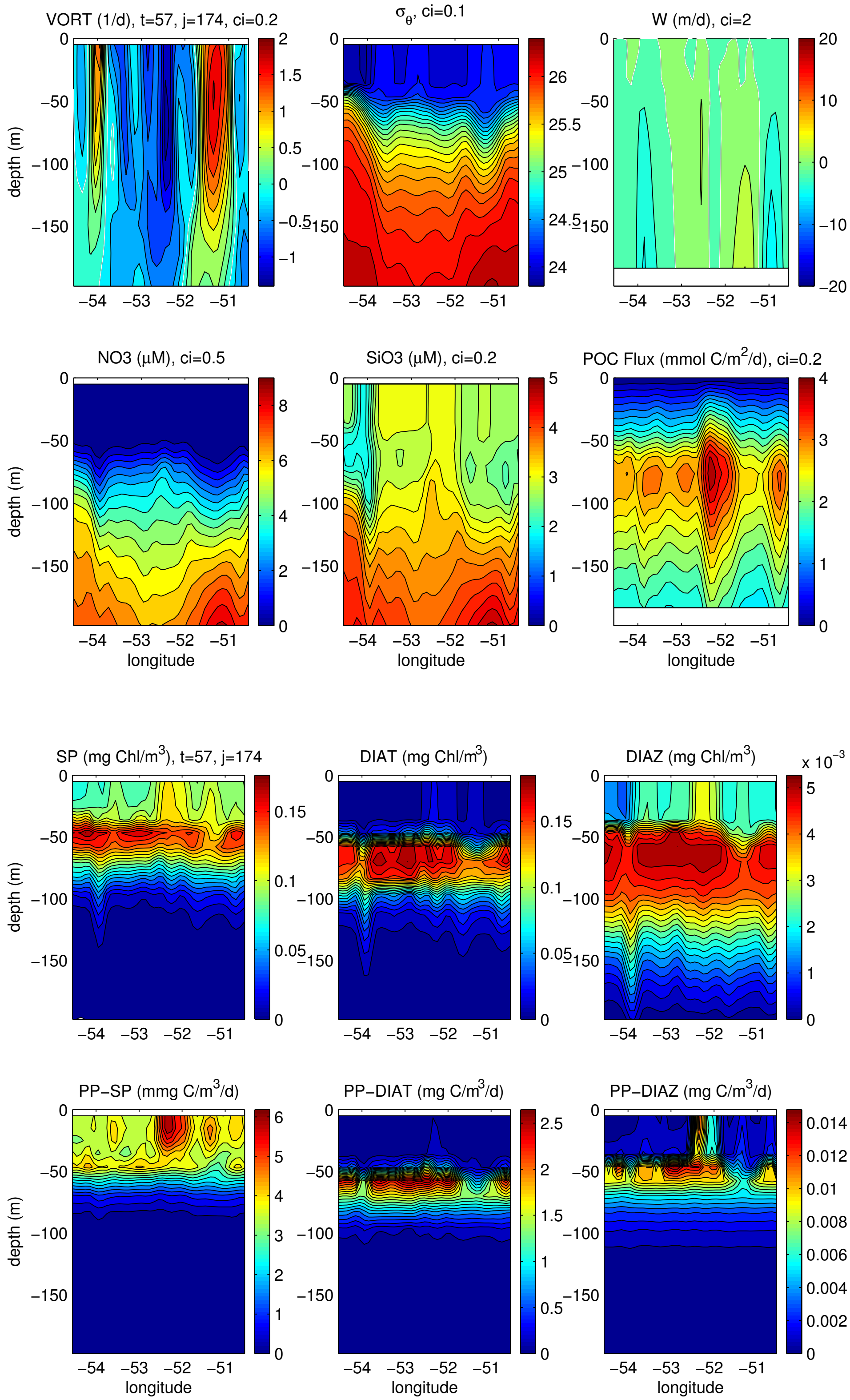
SiO3 (μM), ci=0.2
POC Flux (mmol C/m2/d), ci=0.2
SP (mg Chl/m3), t=57, j=144
DIAT (mg Chl/m3)
DIAZ (mg Chl/m3)
x 10−3
PP−SP (mmg C/m3/d)
PP−DIAT (mg C/m3/d)
PP−DIAZ (mg C/m3/d)
depth (m)
longitude

Fig. 13. Sec. 7.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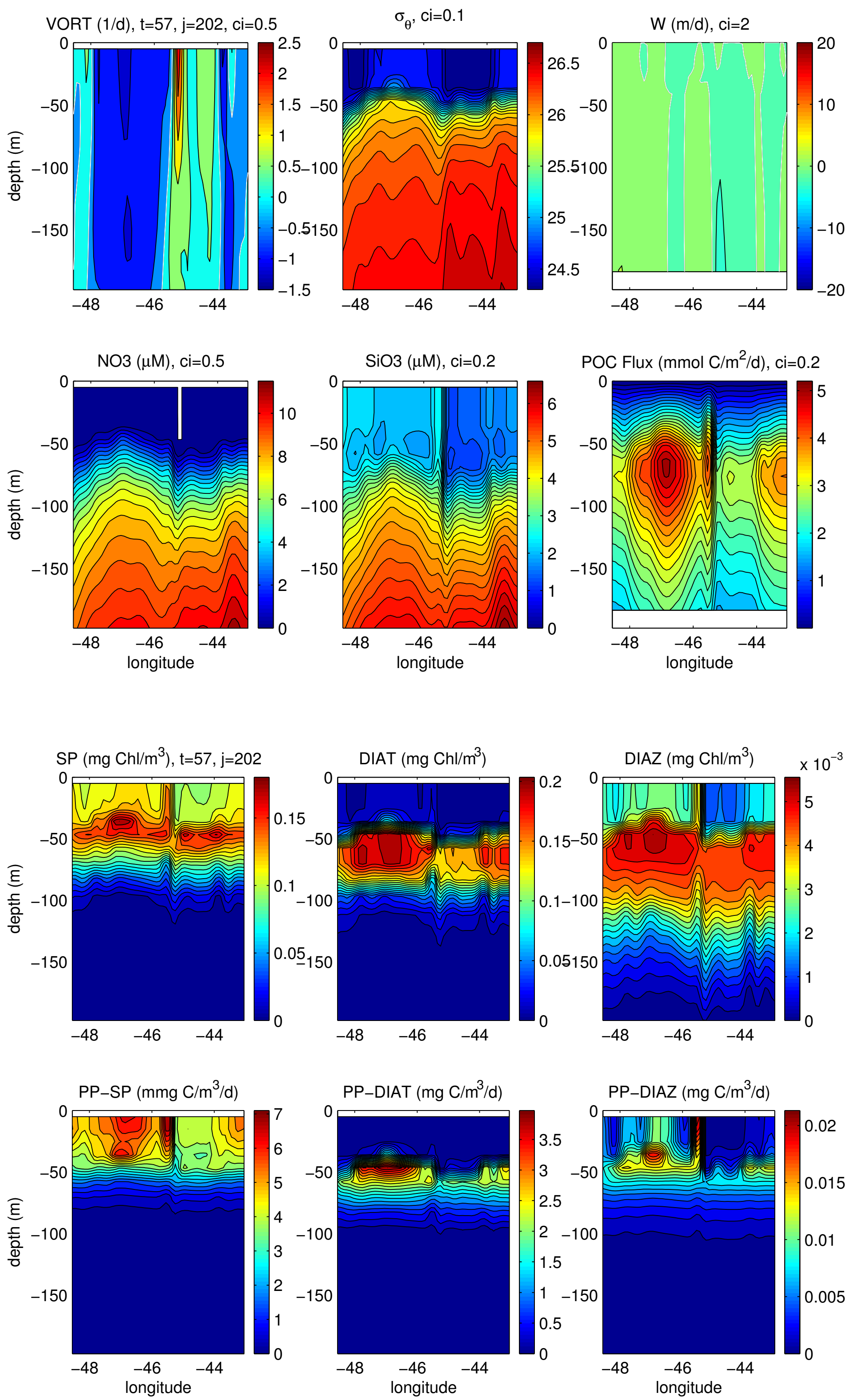
SP (mg Chl/m3), t=57, j=174
DIAT (mg Chl/m3)
DIAZ (mg Chl/m3)
x 10−3
PP−SP (mmg C/m3/d)
PP−DIAT (mg C/m3/d)
PP−DIAZ (mg C/m3/d)
depth (m)
longitude

Fig. 14. Sec. 8.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POC Flux (mmol C/m2/d), ci=0.2
SP (mg Chl/m3), t=57, j=202
DIAT (mg Chl/m3)
DIAZ (mg Chl/m3)
x 10−3
PP−SP (mmg C/m3/d)
PP−DIAT (mg C/m3/d)
PP−DIAZ (mg C/m3/d)
depth (m)
longitude

Fig. 15. Sec. 9.

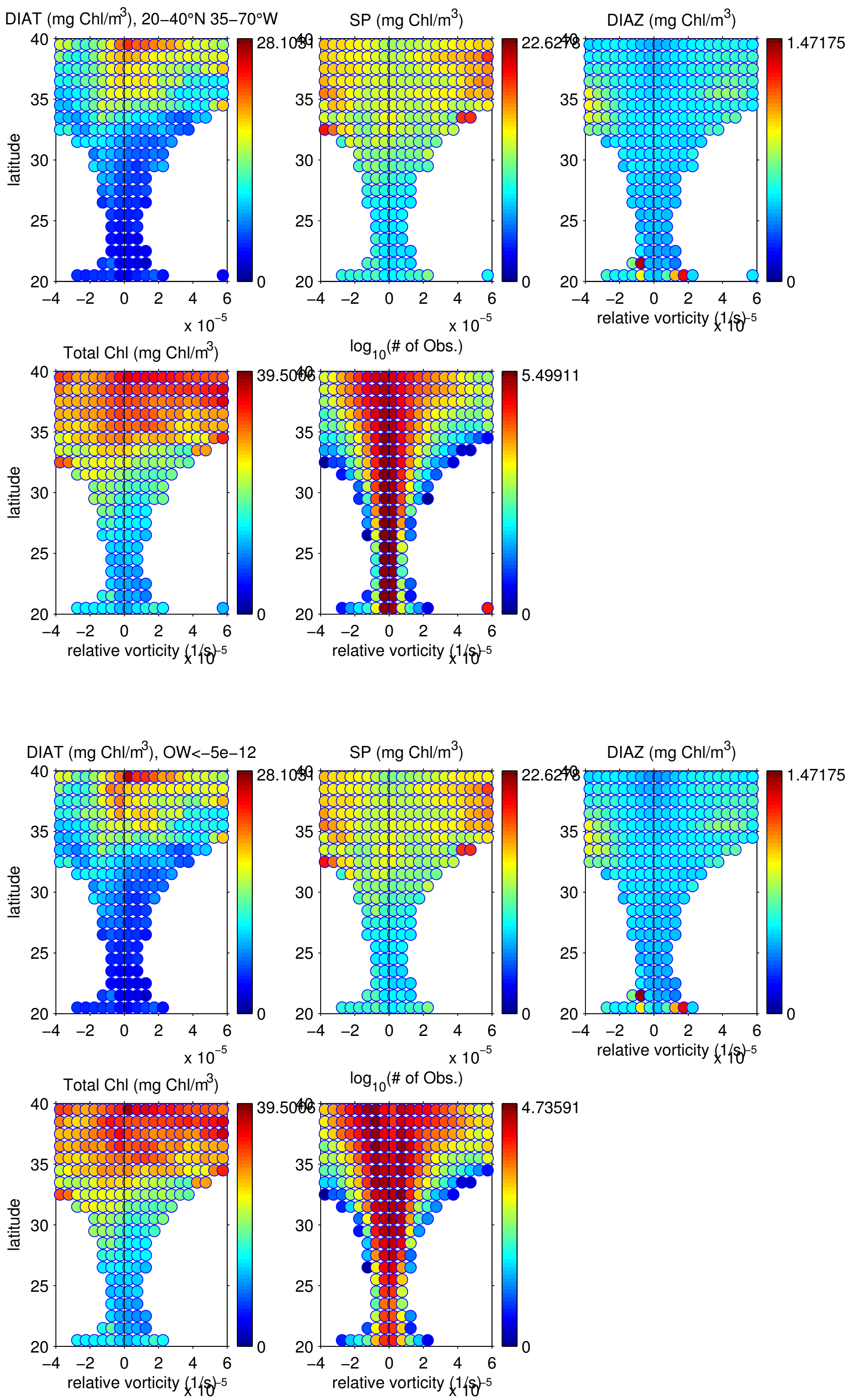


Fig. 16. all year, (a) all grid points, (b) eddies only.

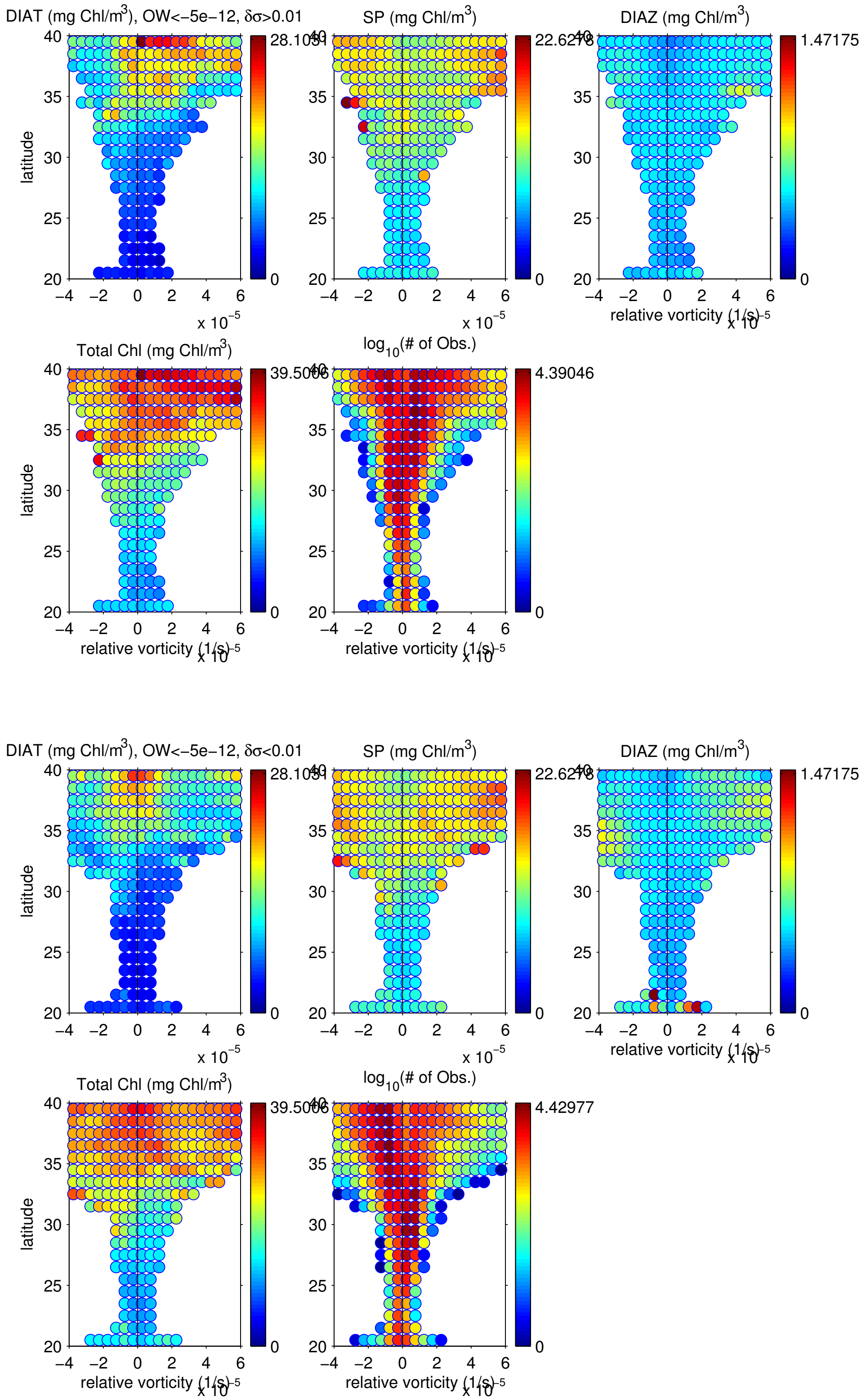


Fig. 17. all year, (a) MWE and cyclones, (b) AC and Thinnies.

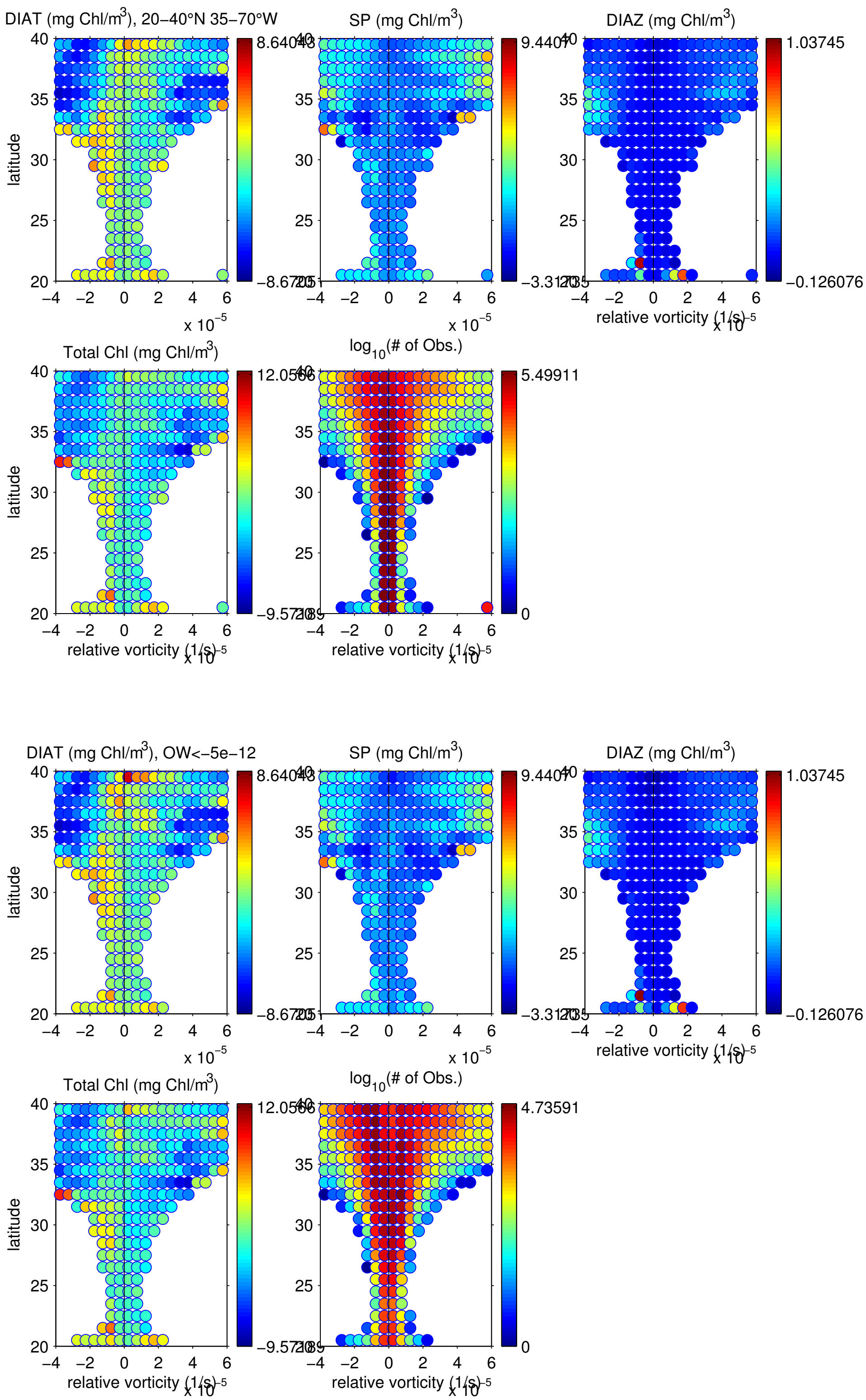


Fig. 18. all year, (a) all grid points, (b) eddies only.

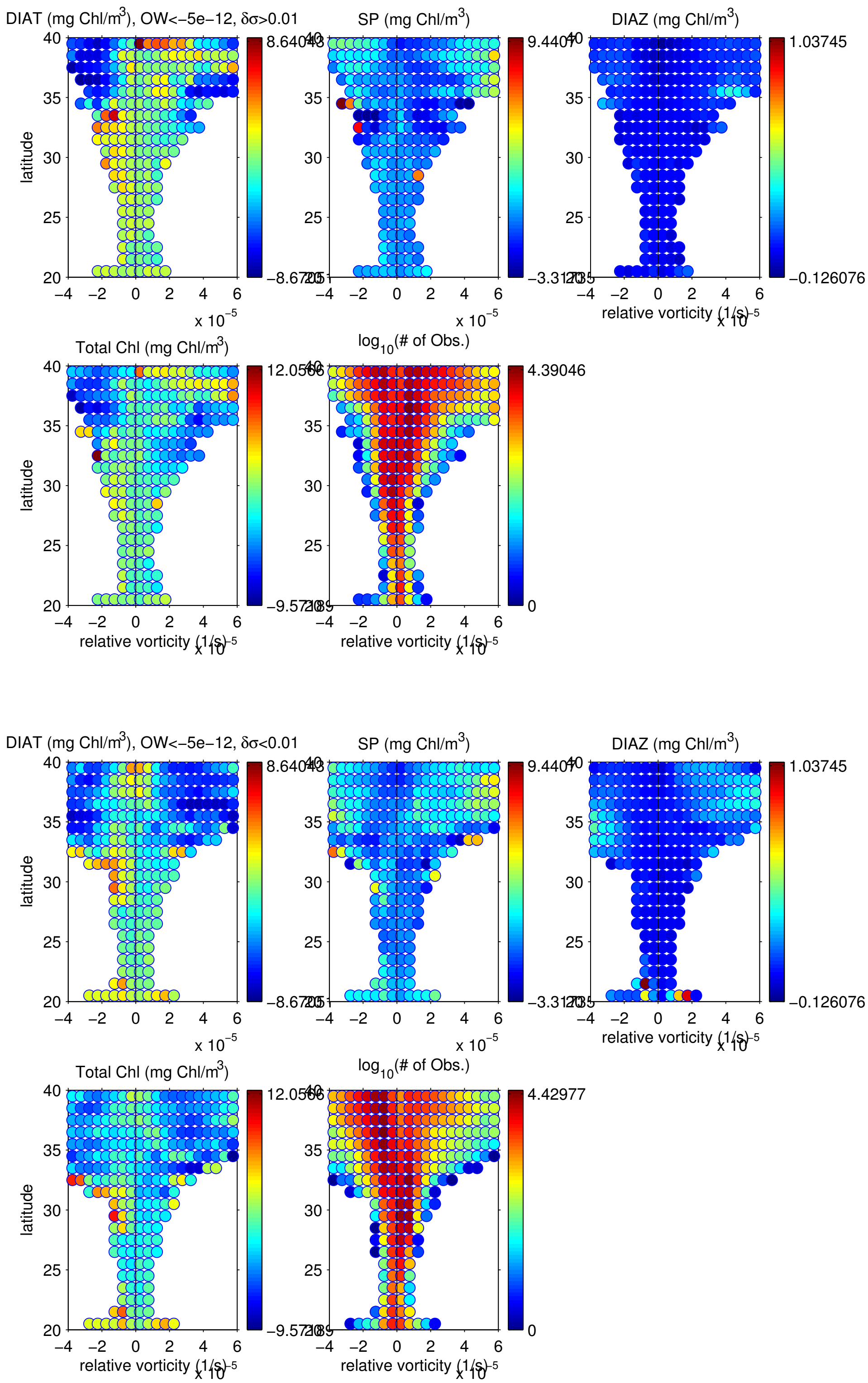


Fig. 19. all year, (a) MWE and cyclones, (b) AC and Thinnies.

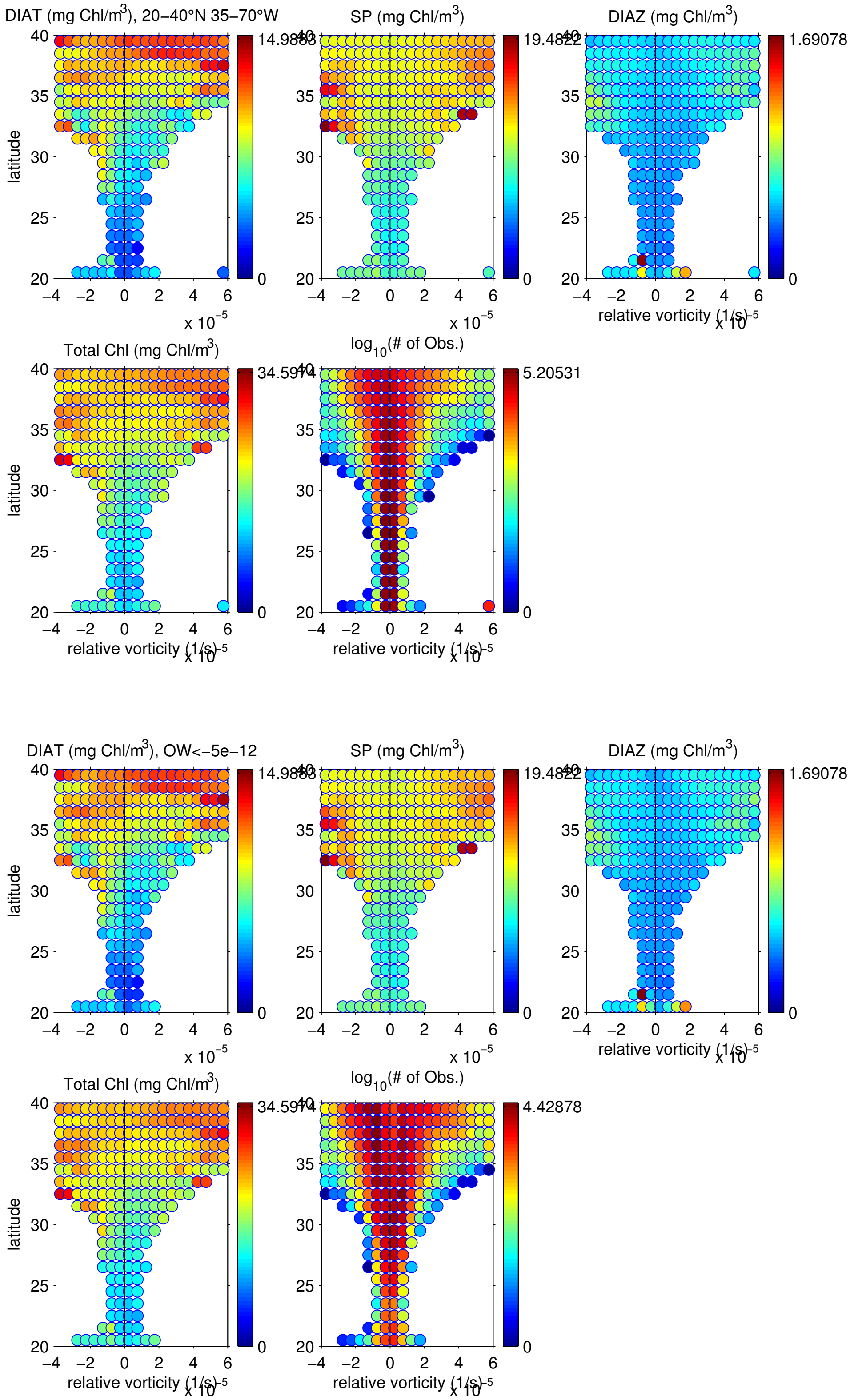


Fig. 20. summer only, (a) all grid points, (b) eddies only.

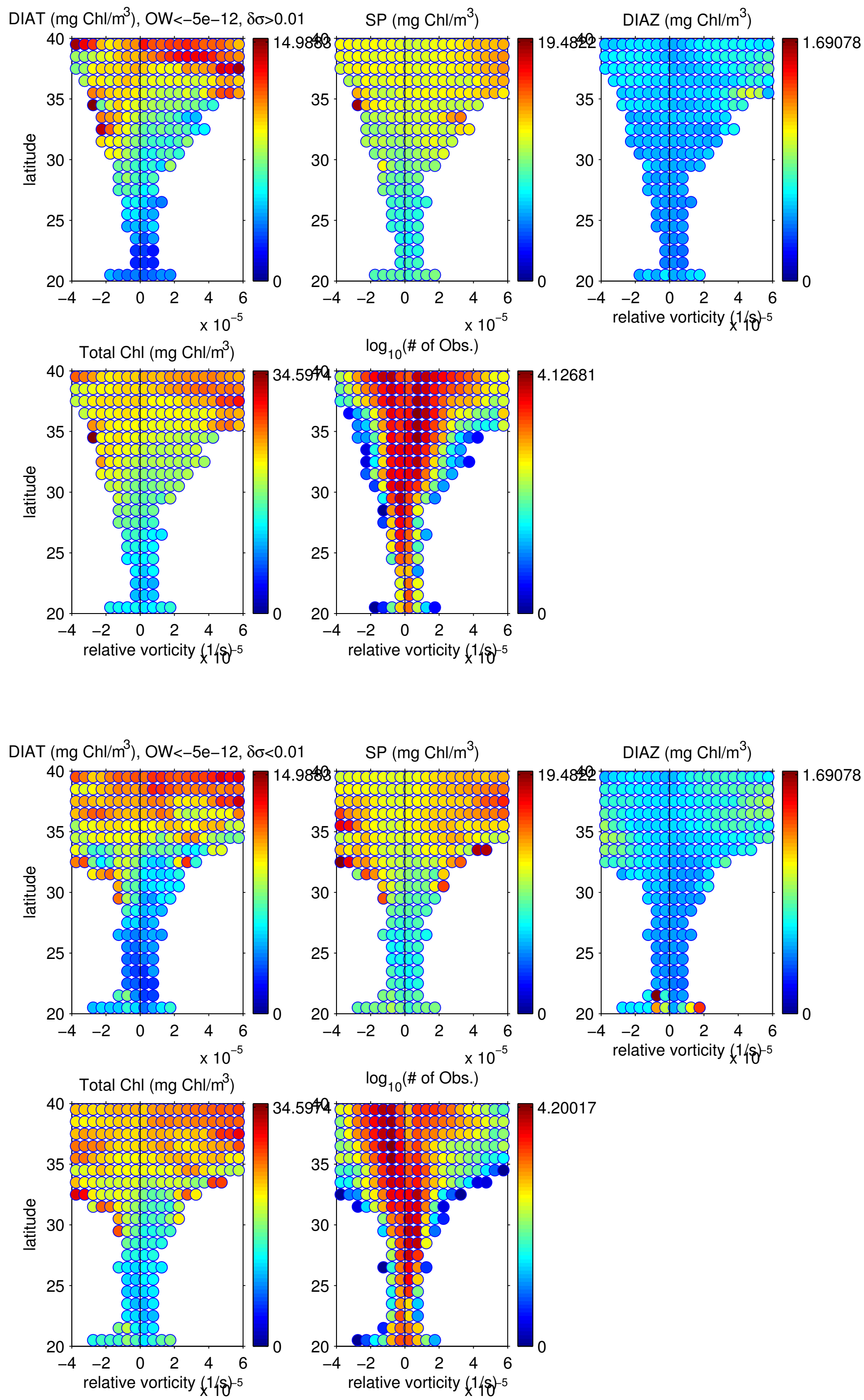


Fig. 21. summer only, (a) MWE and cyclones, (b) AC and Thinnies.

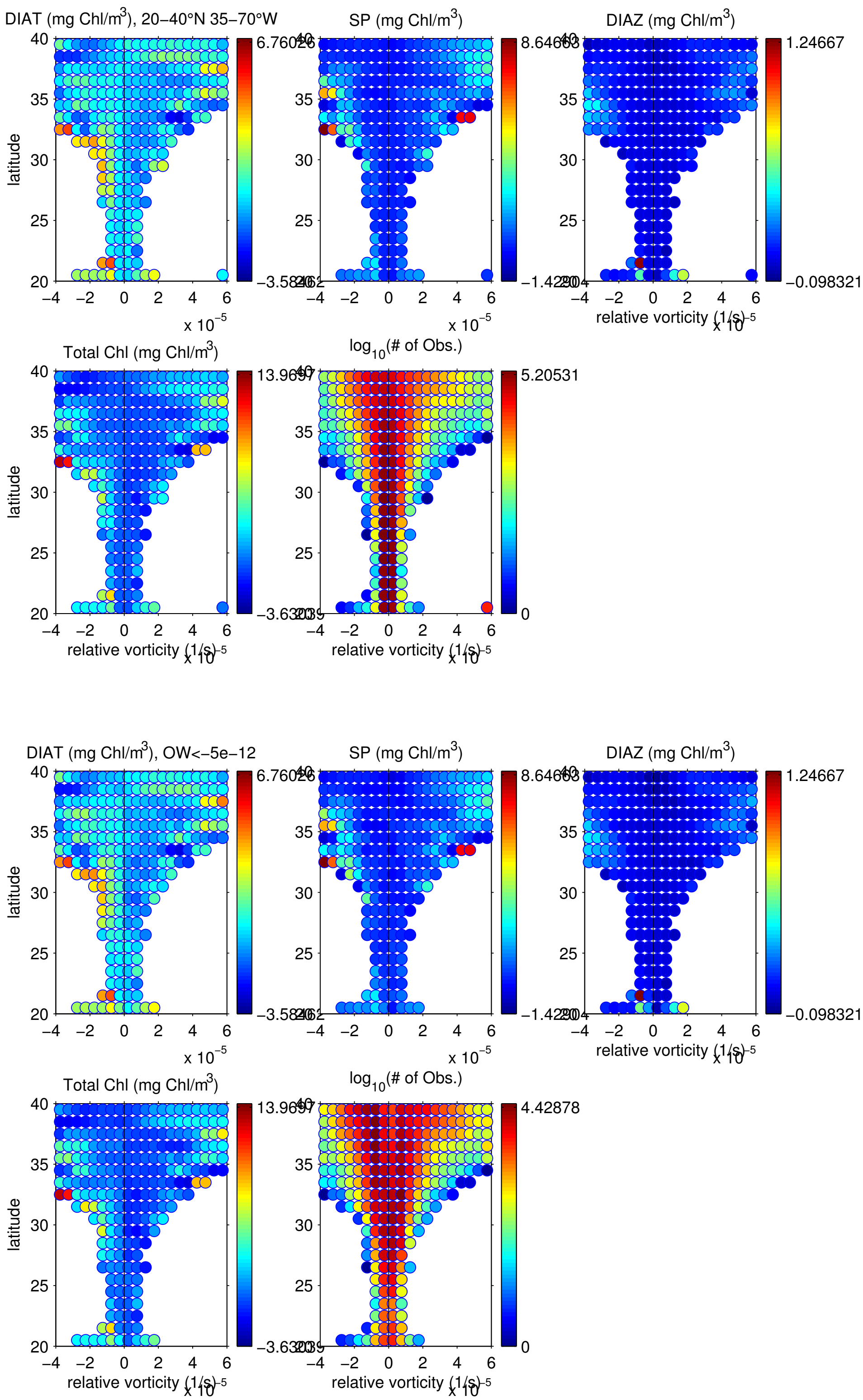


Fig. 22. summer only, (a) all grid points, (b) eddies only.

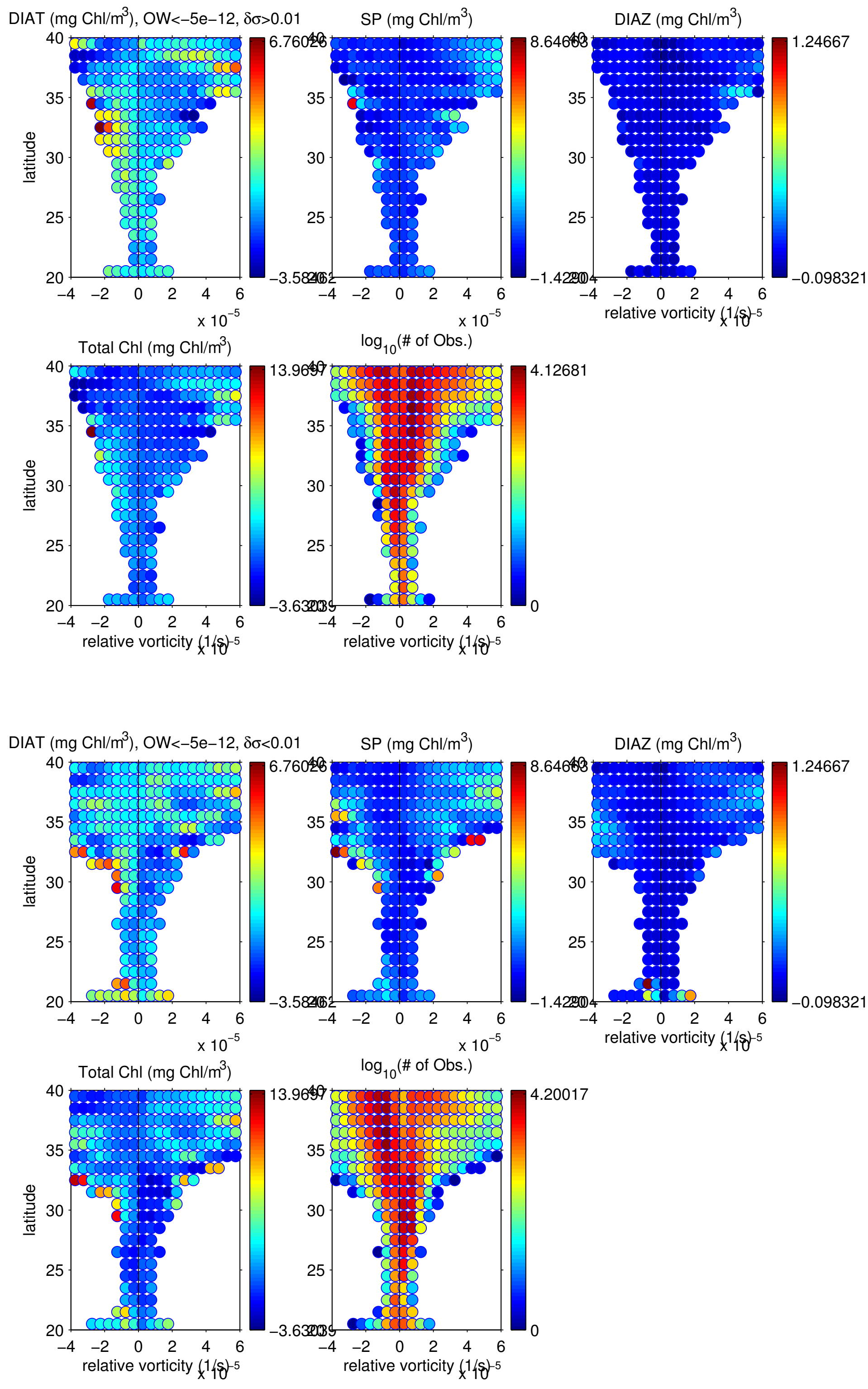


Fig. 23. summer only, (a) MWE and cyclones, (b) AC and Thinnies.

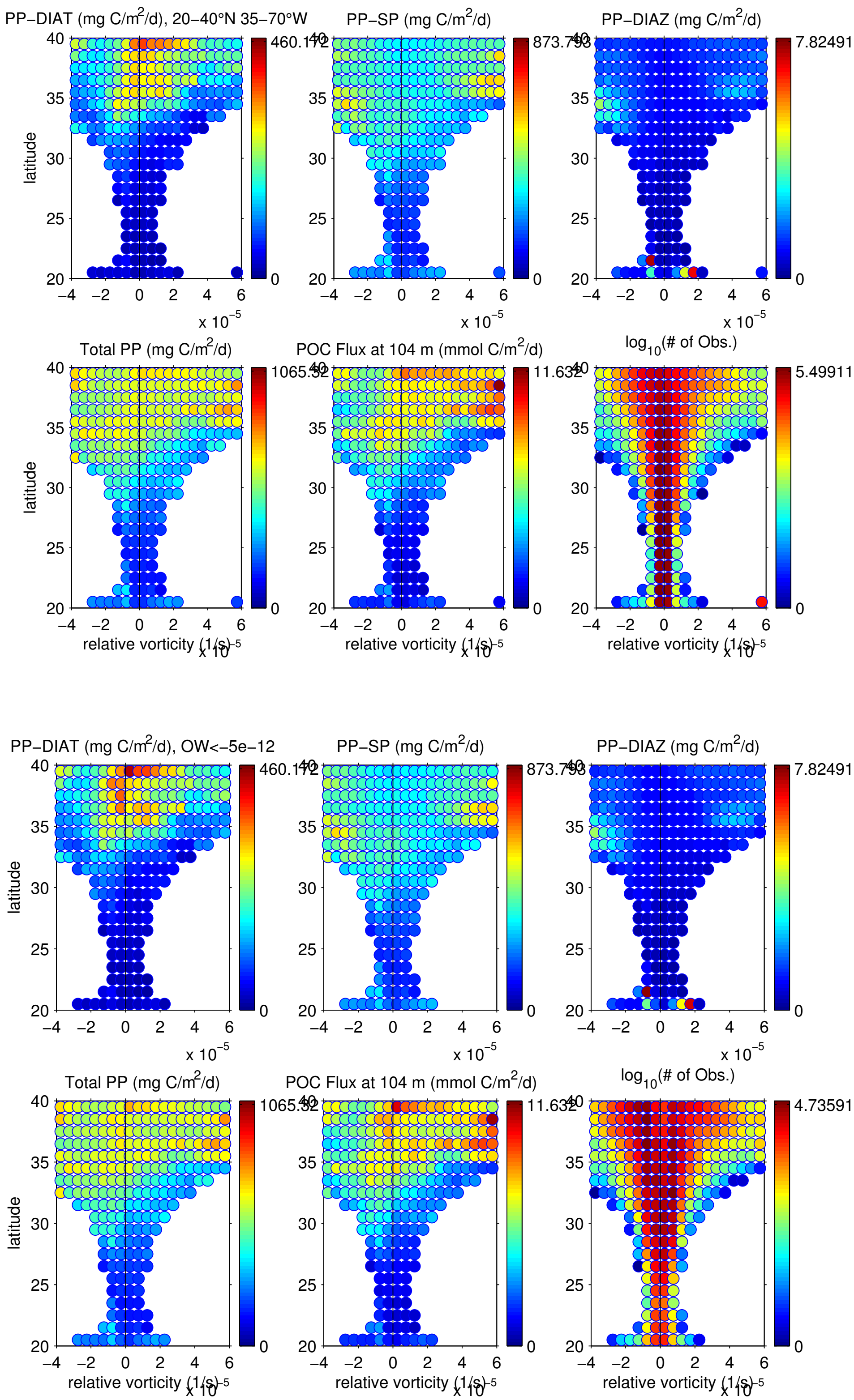


Fig. 24. all year, (a) all grid points, (b) eddies only.

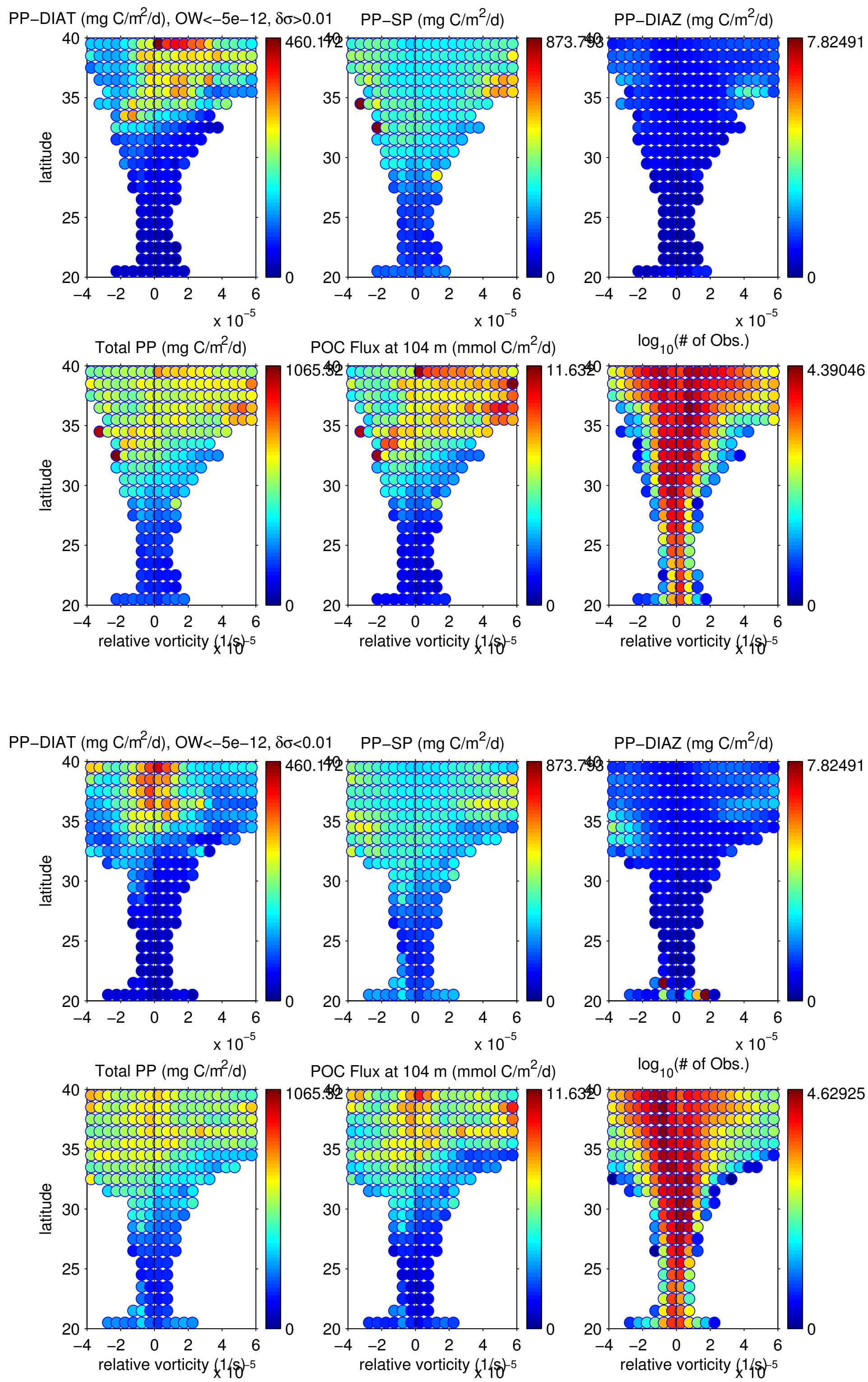


Fig. 25. all year, (a) MWE and cyclones, (b) AC and Thinnies.

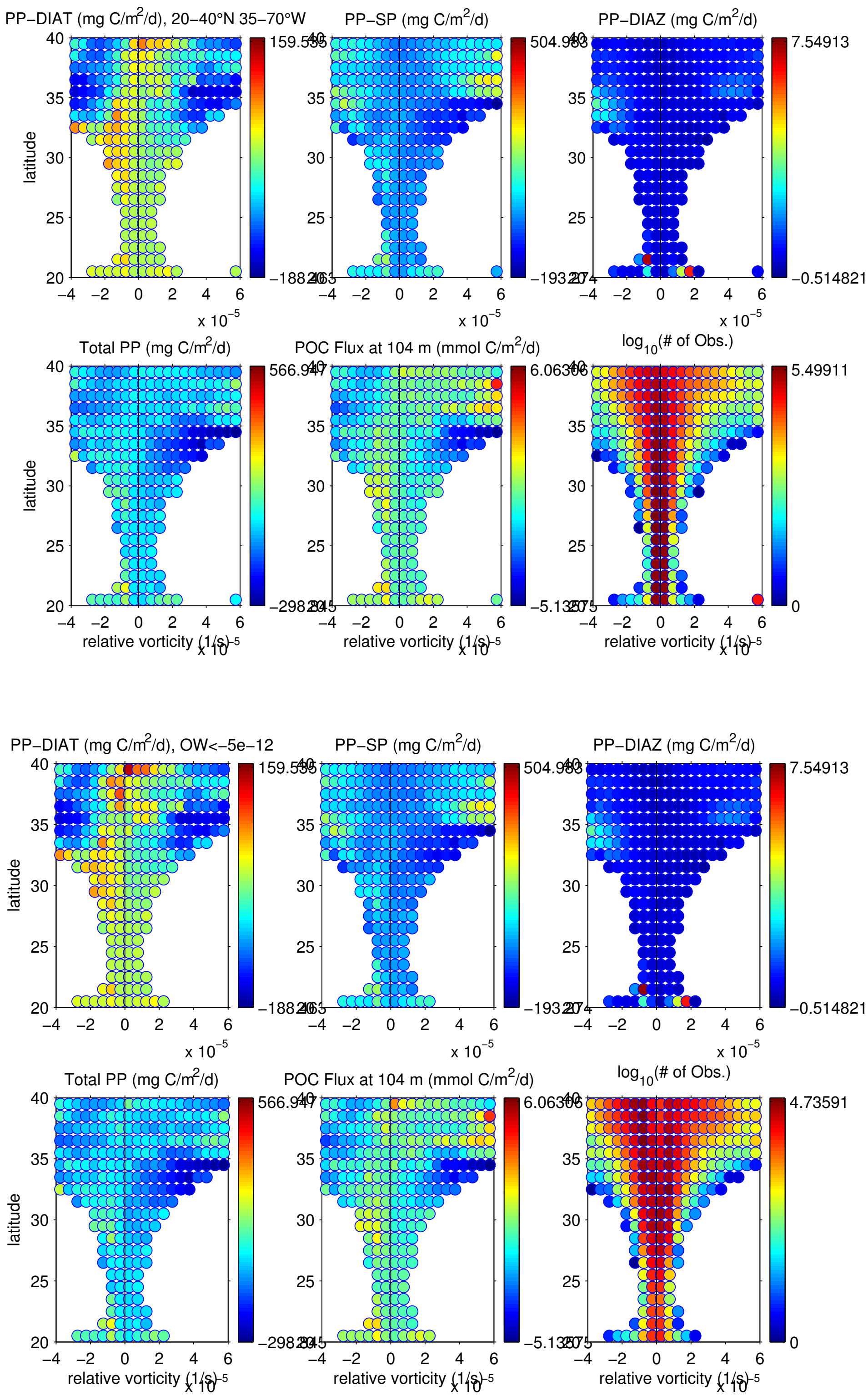


Fig. 26. all year, (a) all grid points, (b) eddies only.

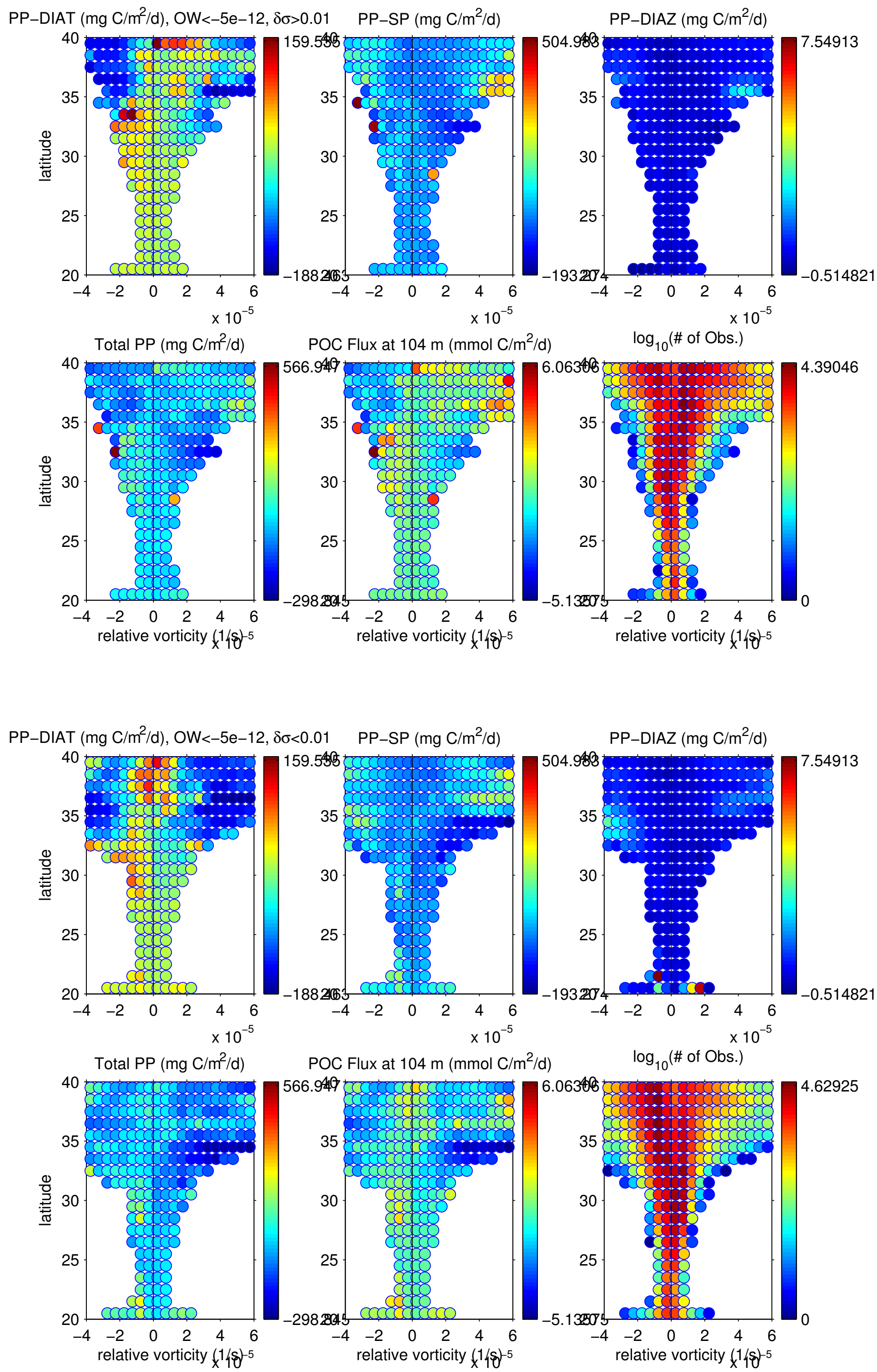
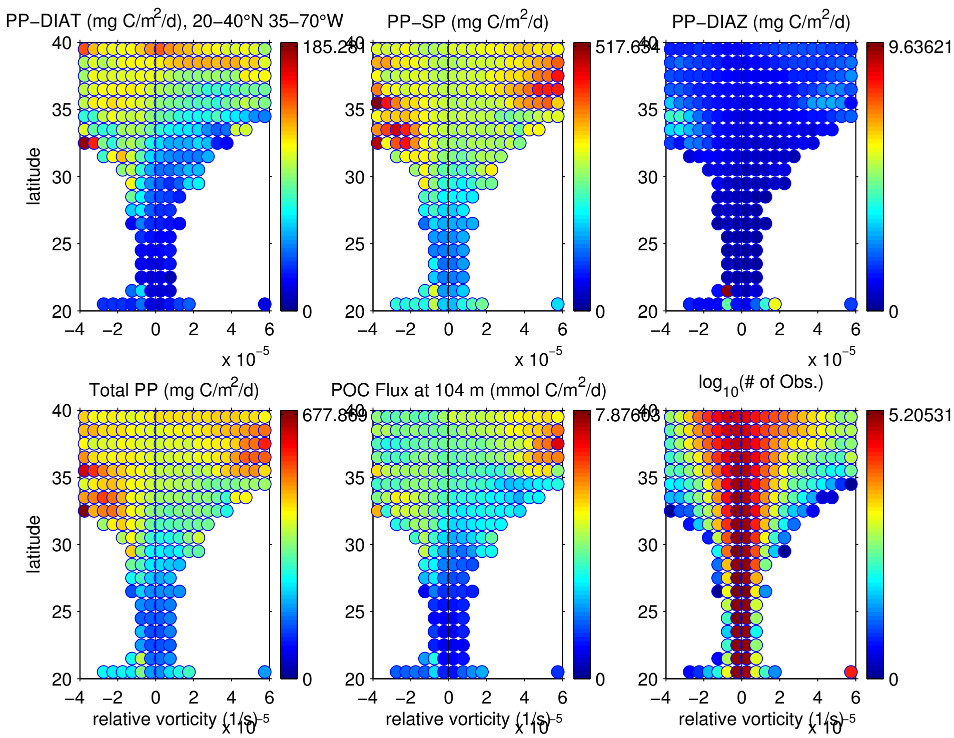


Fig. 27. all year, (a) MWE and cyclones, (b) AC and Thinnies.



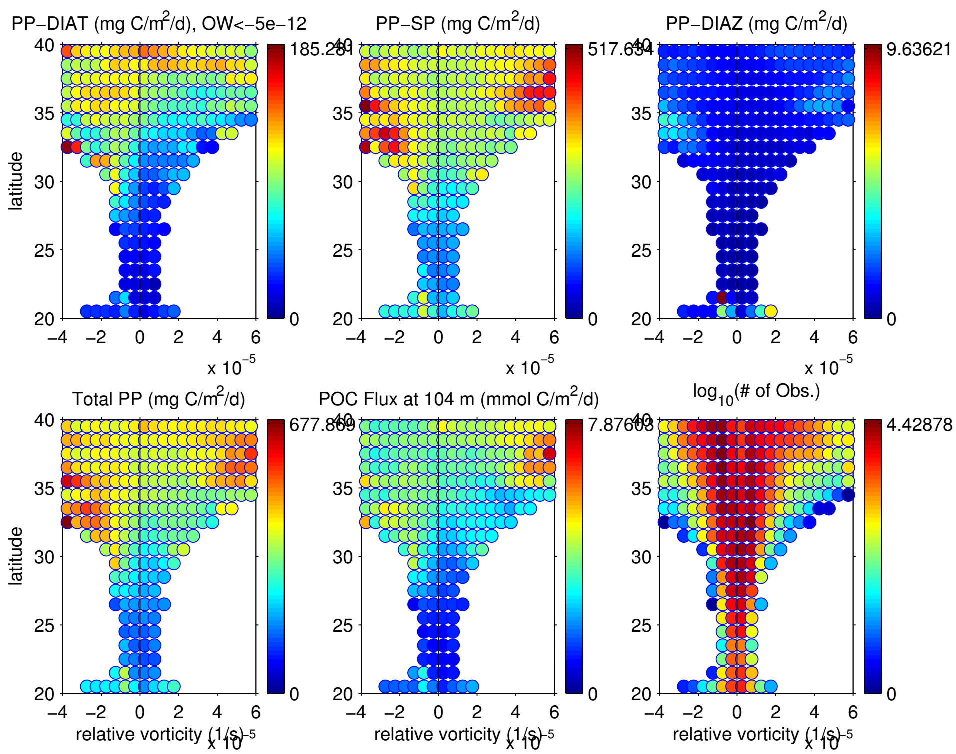


Fig. 28. summer only, (a) all grid points, (b) eddies only.

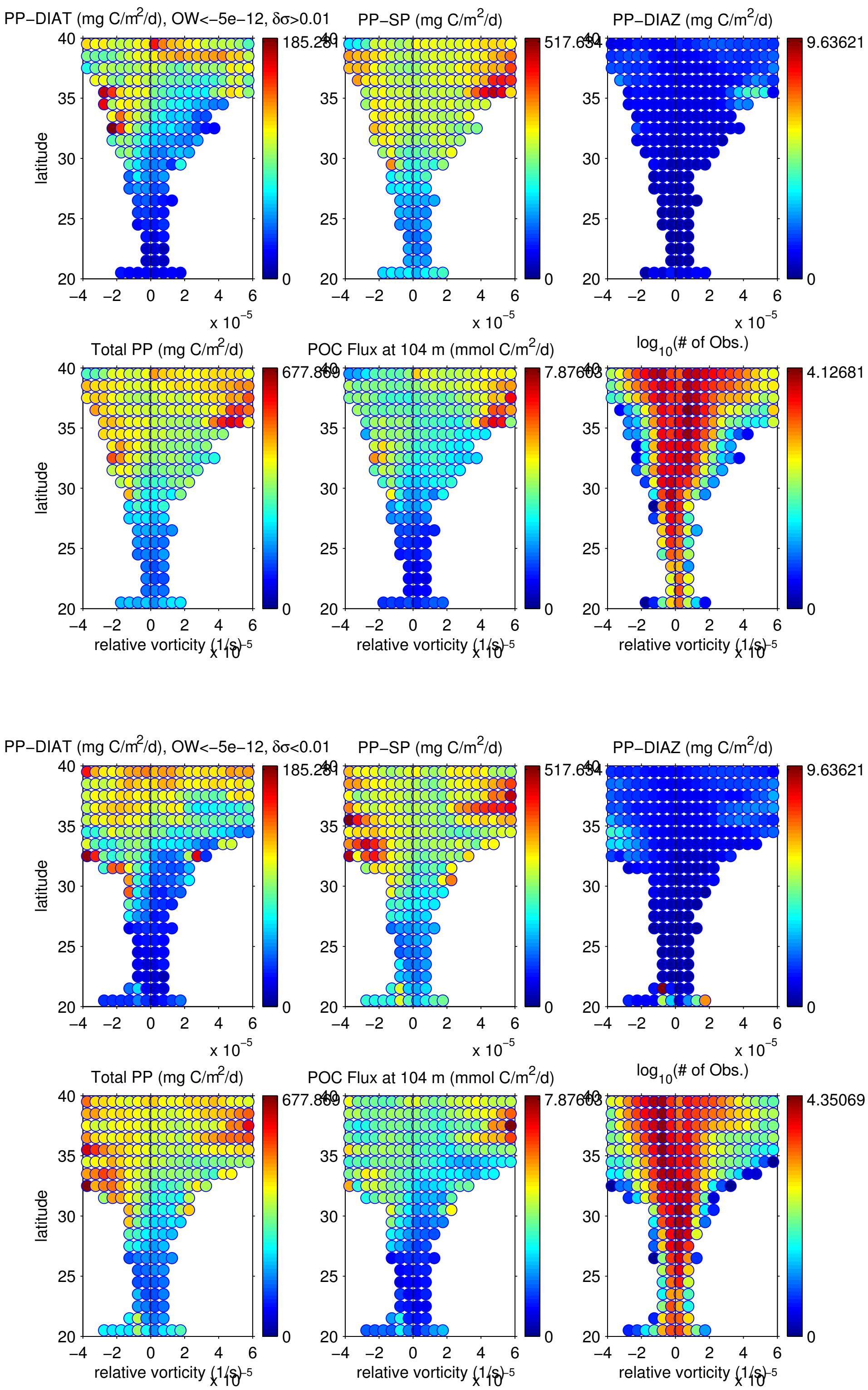


Fig. 29. summer only, (a) MWE and cyclones, (b) AC and Thinnies.

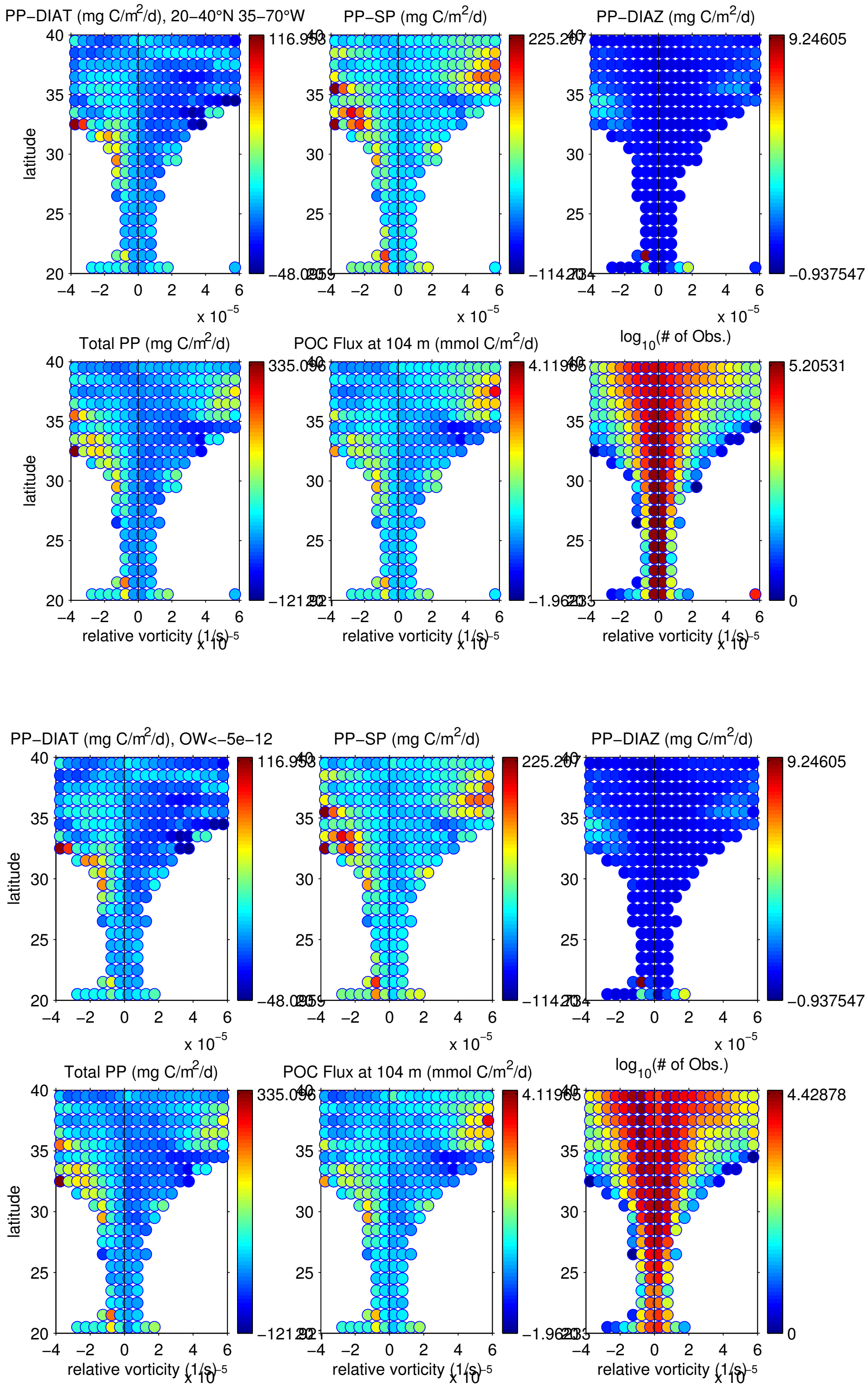


Fig. 30. summer only, (a) all grid points, (b) eddies only.

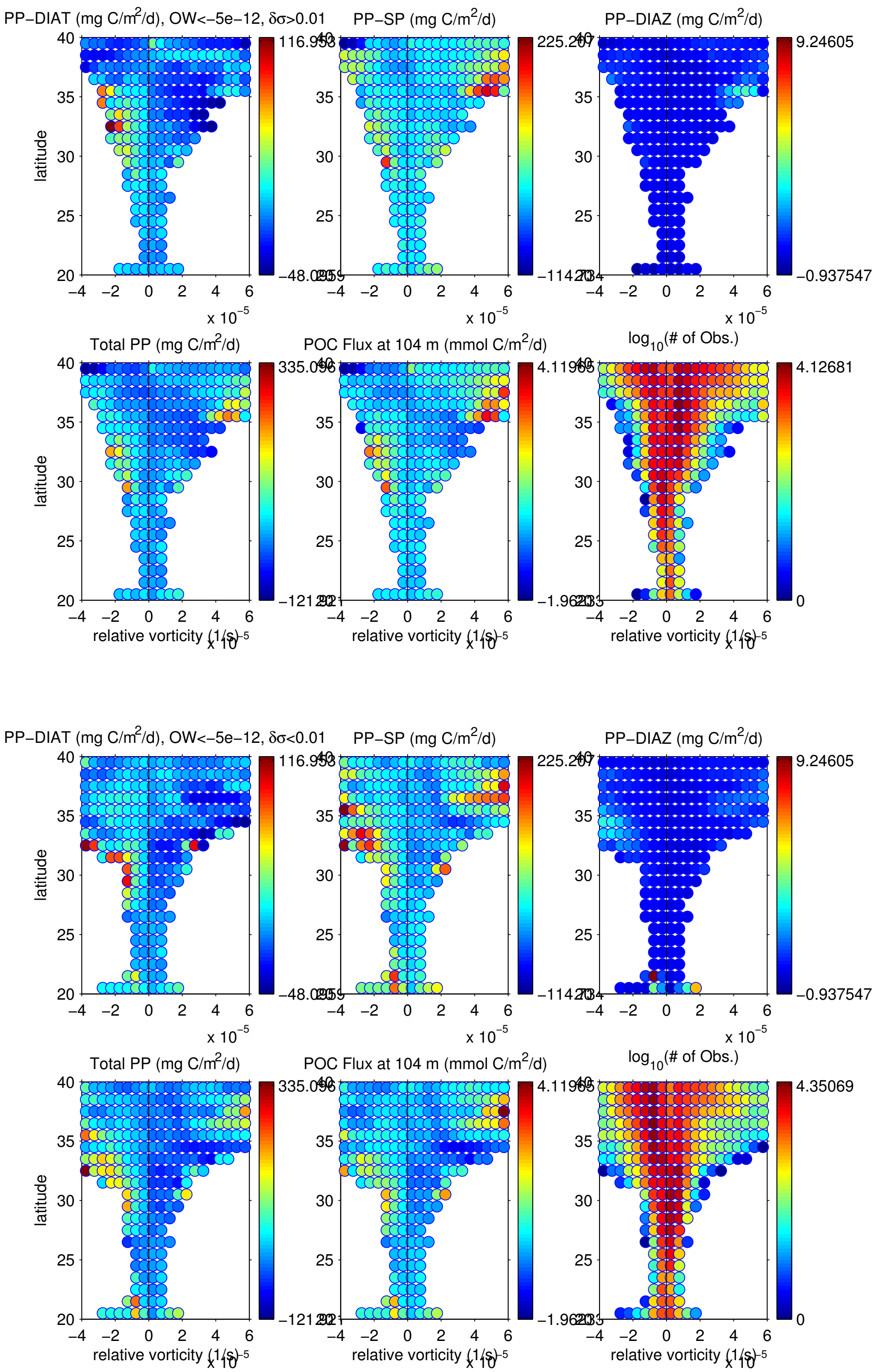


Fig. 31. summer only, (a) MWE and cyclones, (b) AC and Thinnies.

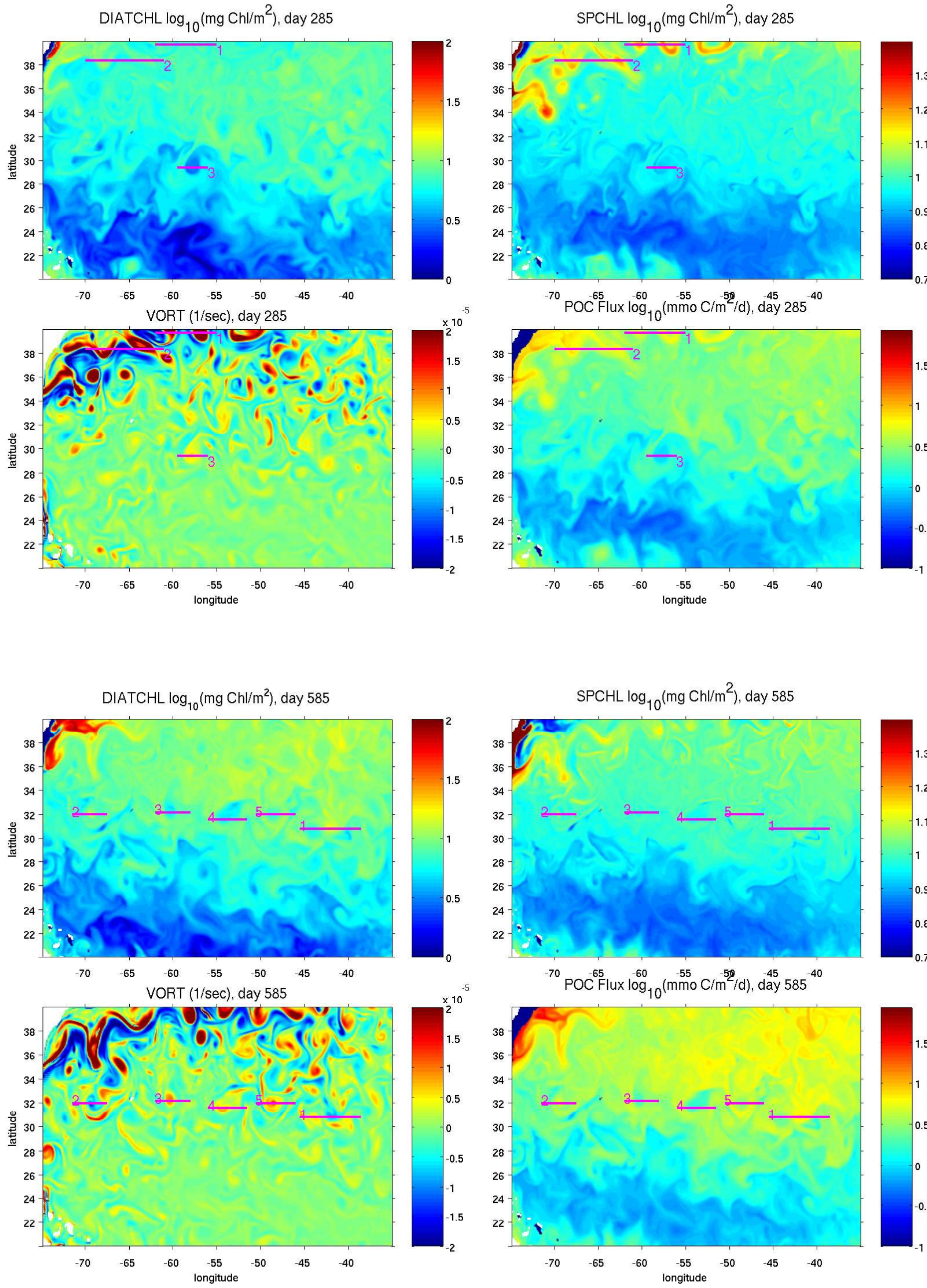


Fig. 32. summer snapshots (a) day 285, (b) day 585.

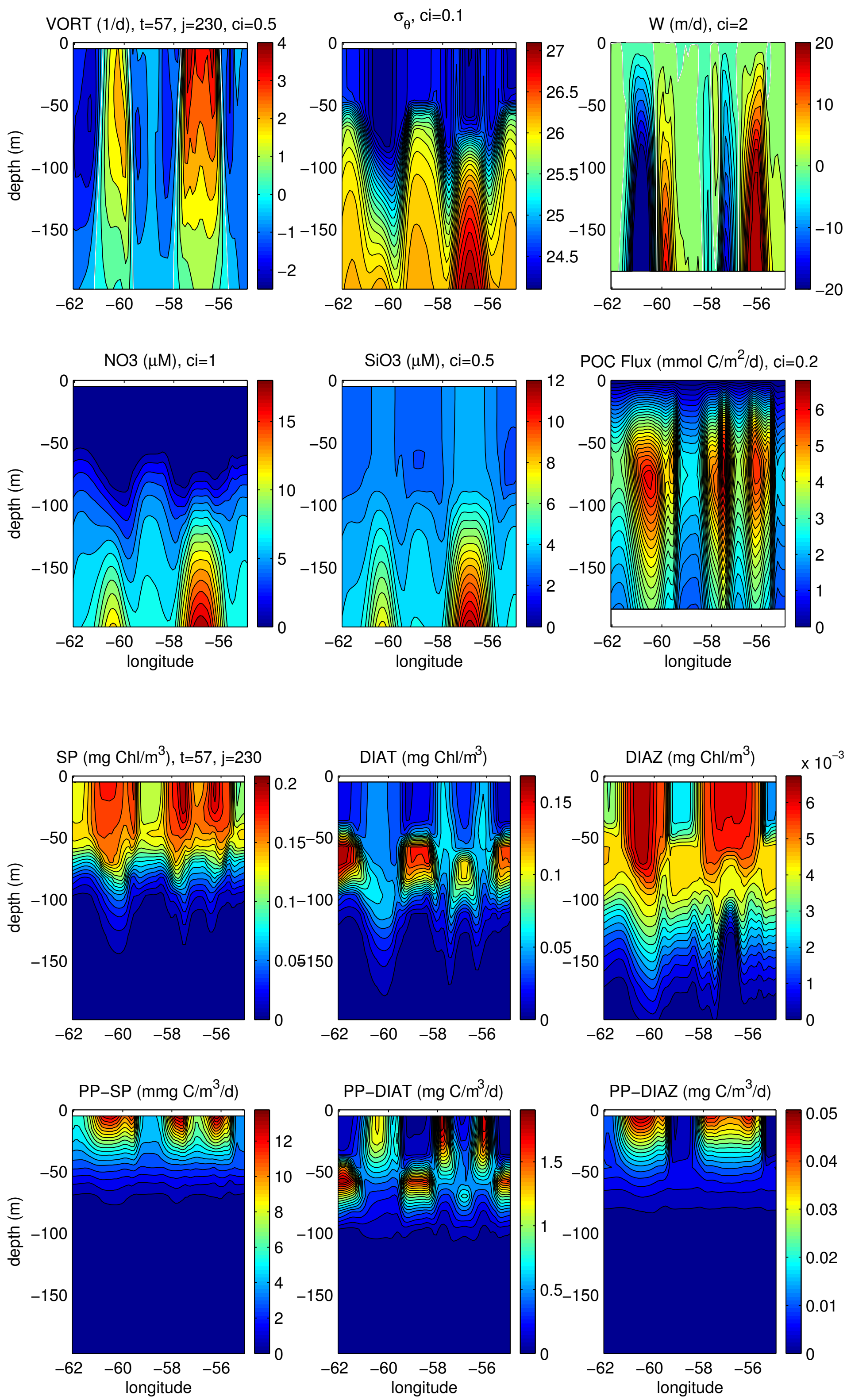


Fig. 33. Day 285 Section 1.

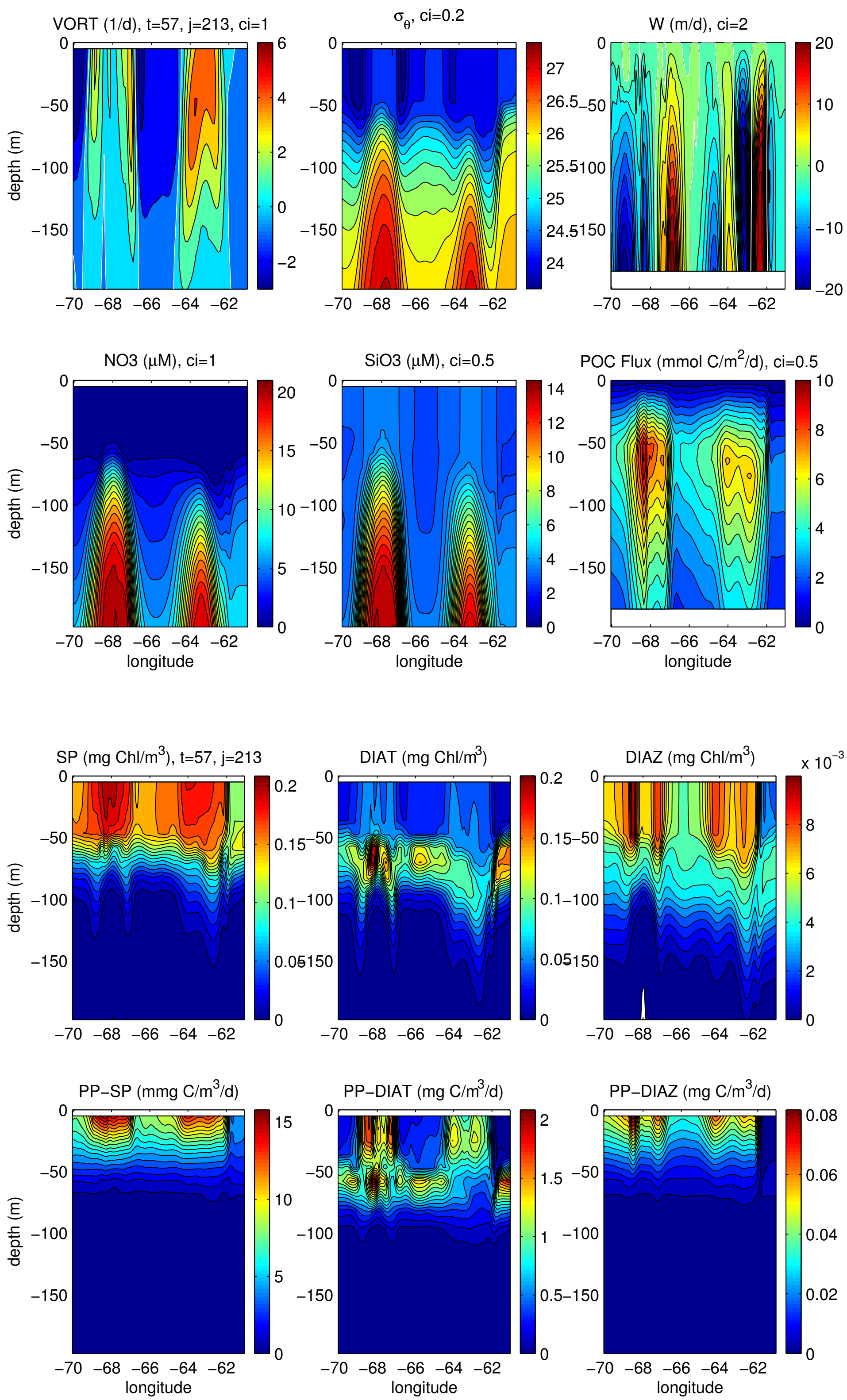


Fig. 34. Day 285 Section 2.

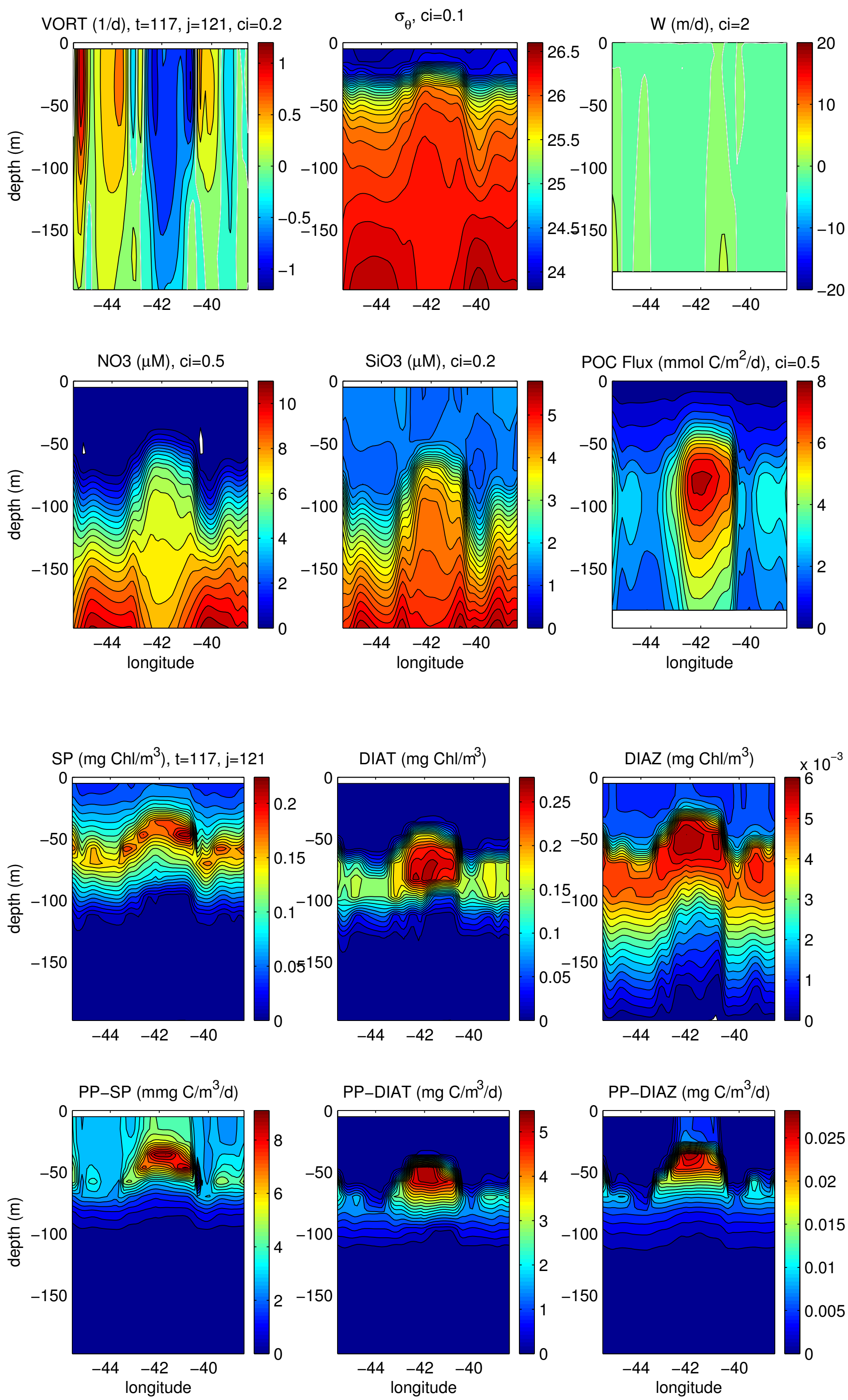


Fig. 35. Day 585 Section 1.

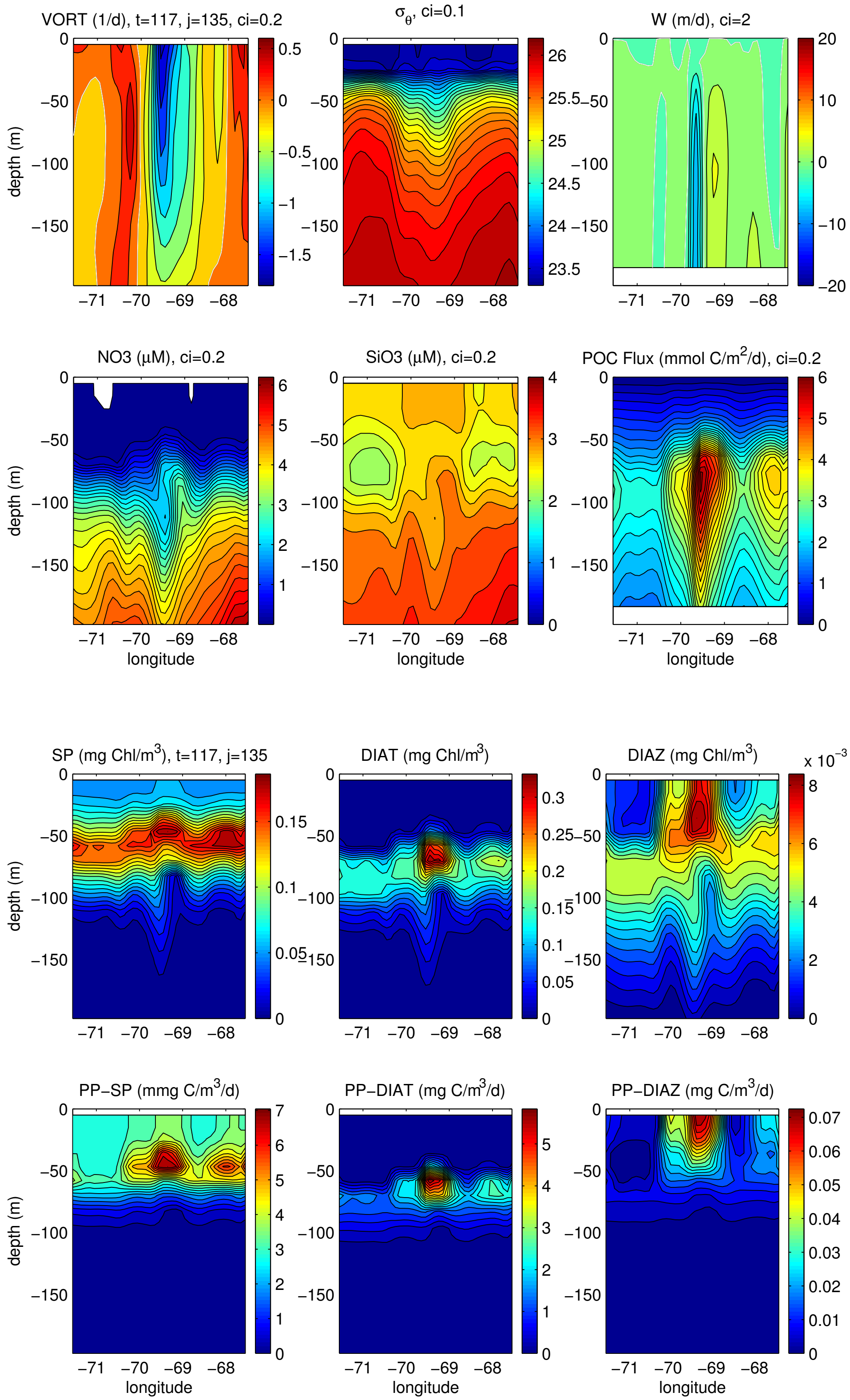


Fig. 36. Day 585 Section 2.

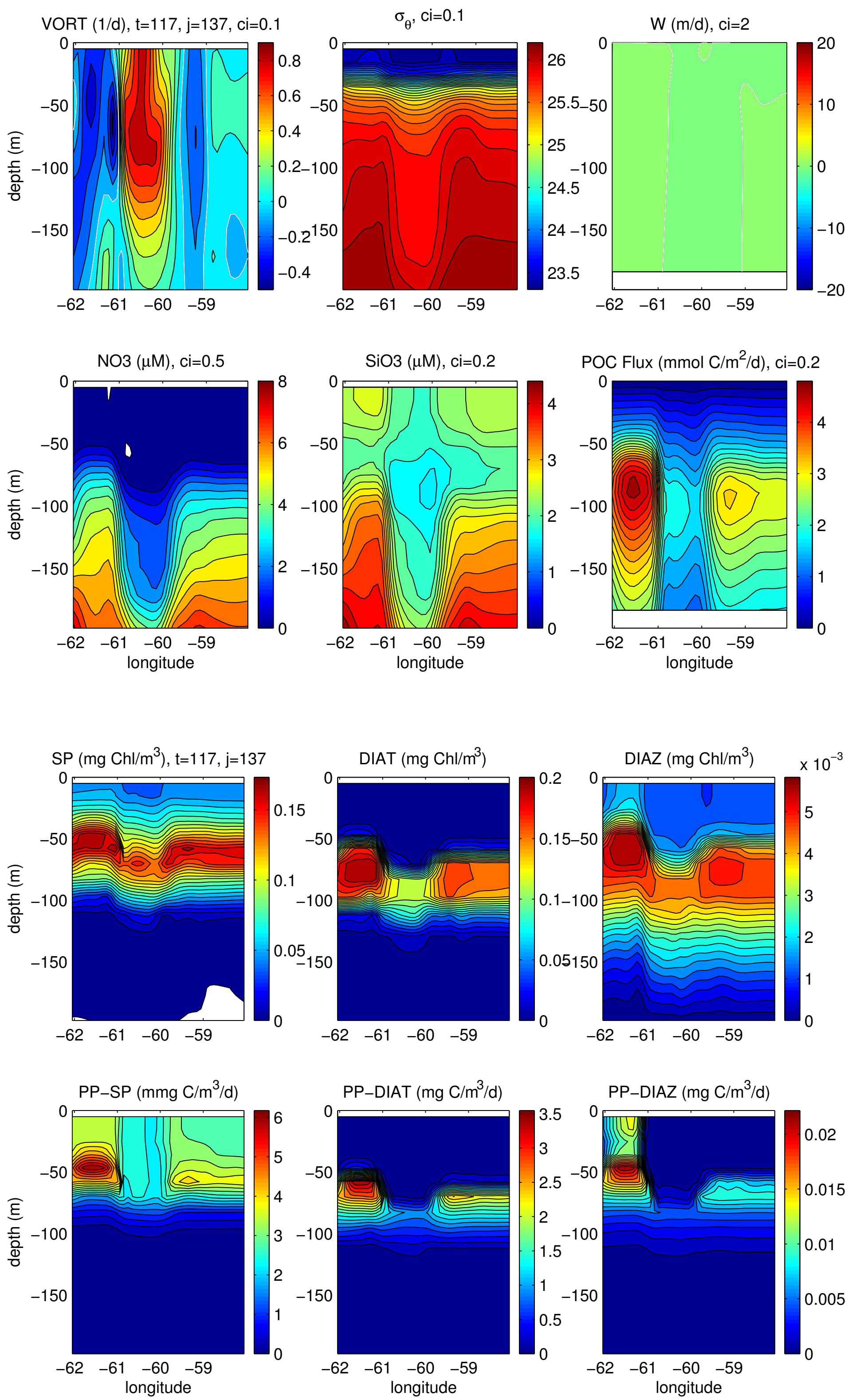


Fig. 37. Day 585 Section 3.

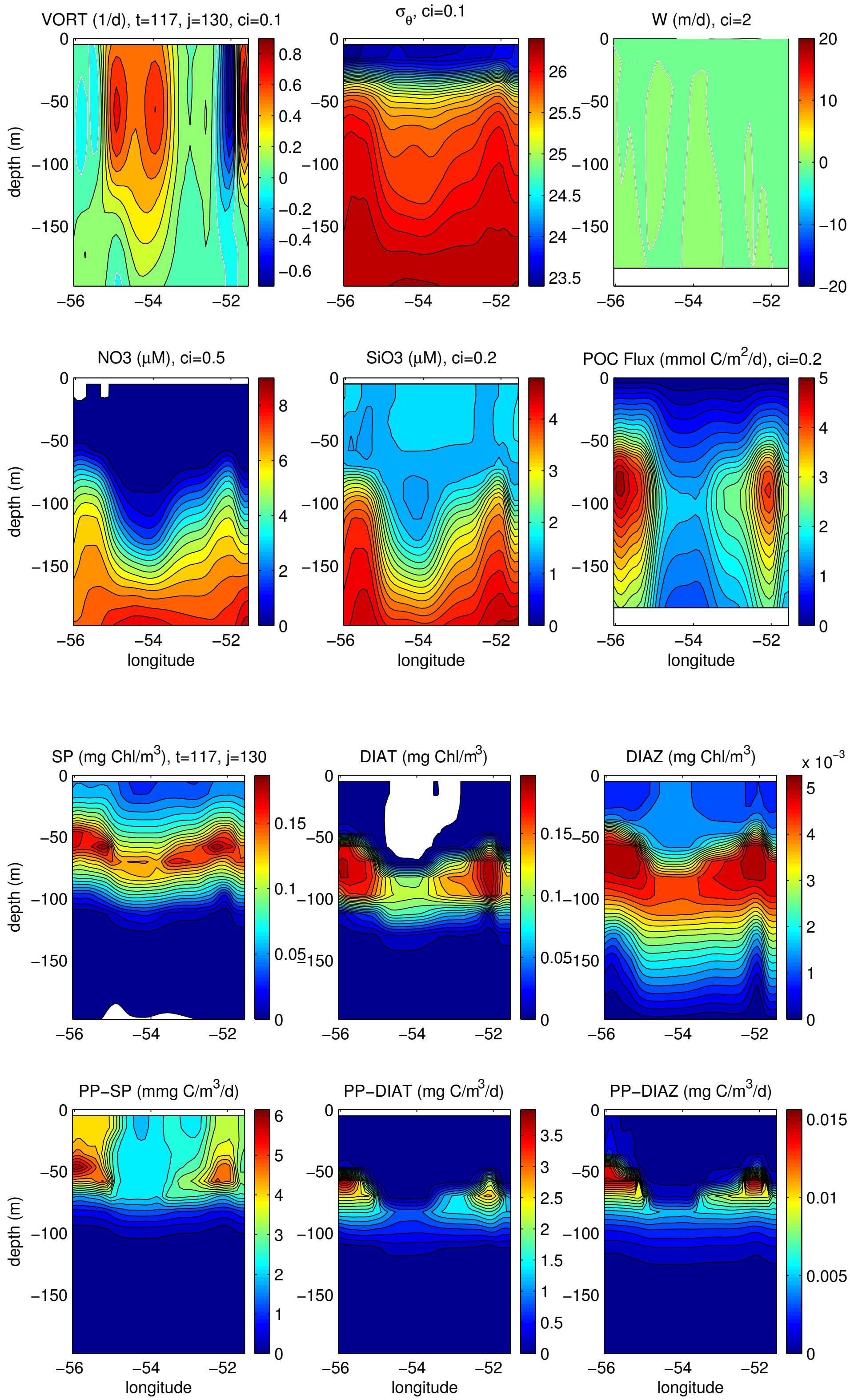


Fig. 38. Day 585 Section 4.

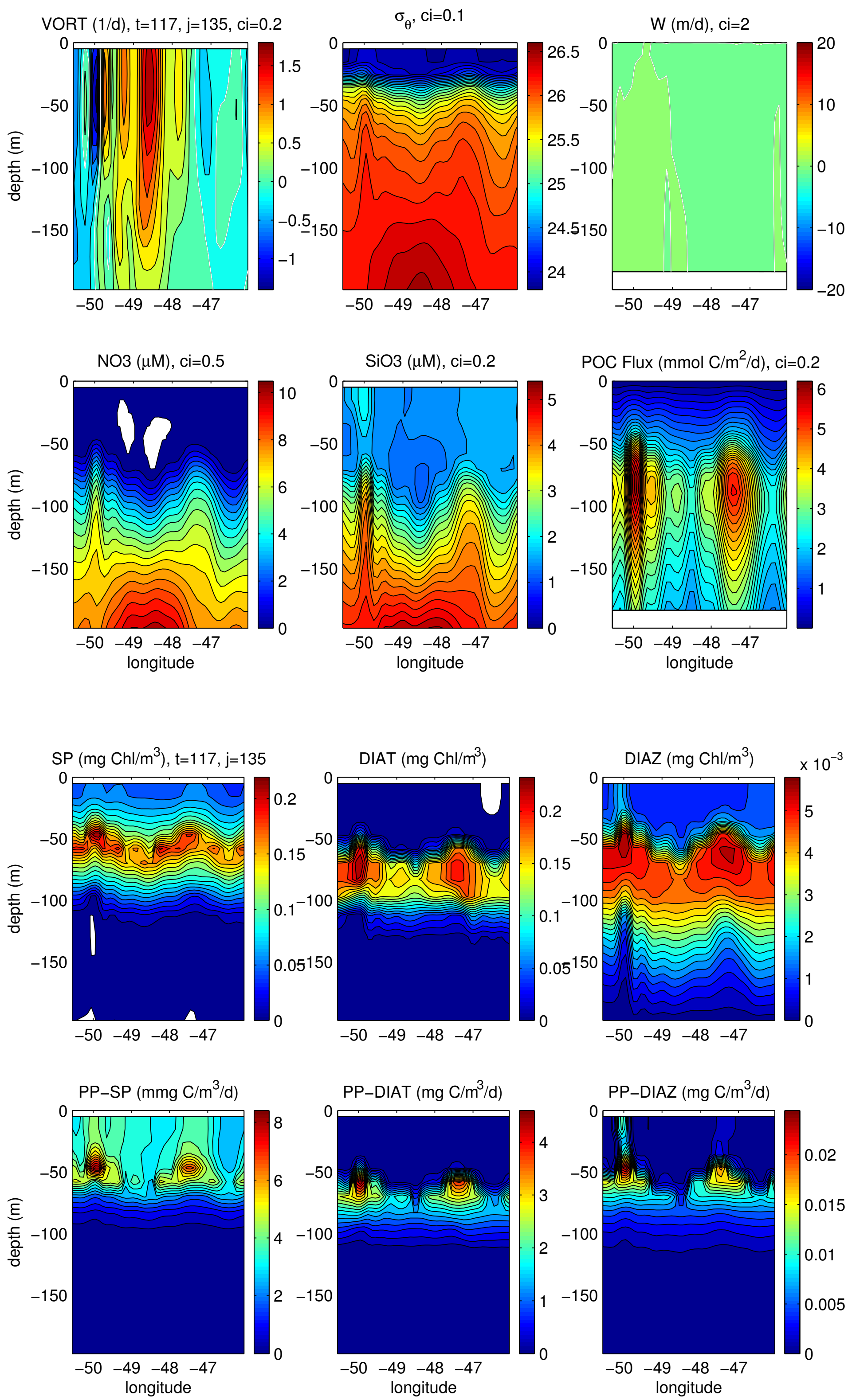


Fig. 39. Day 585 Section 5.