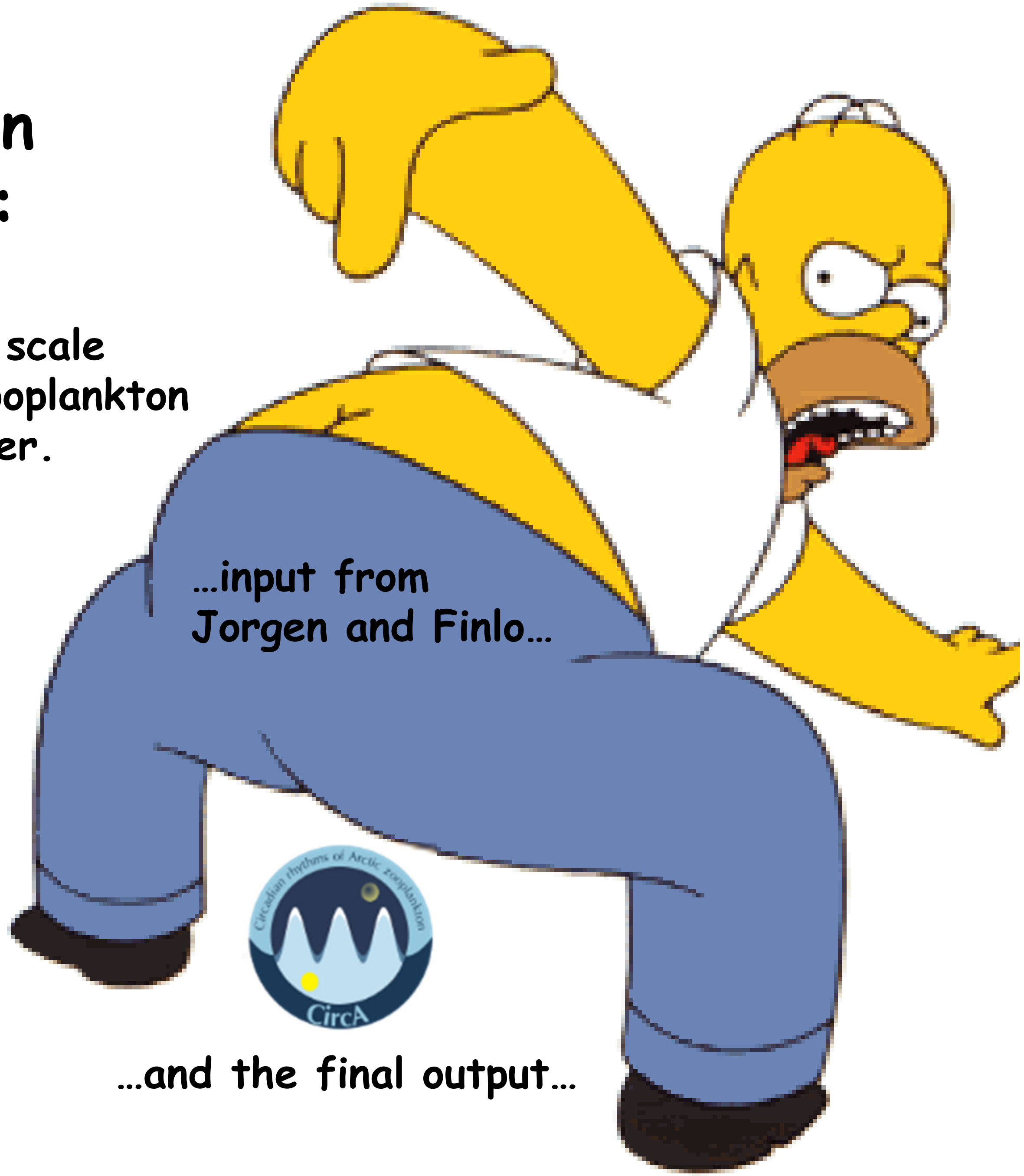
# Where the sun doesn't shine:

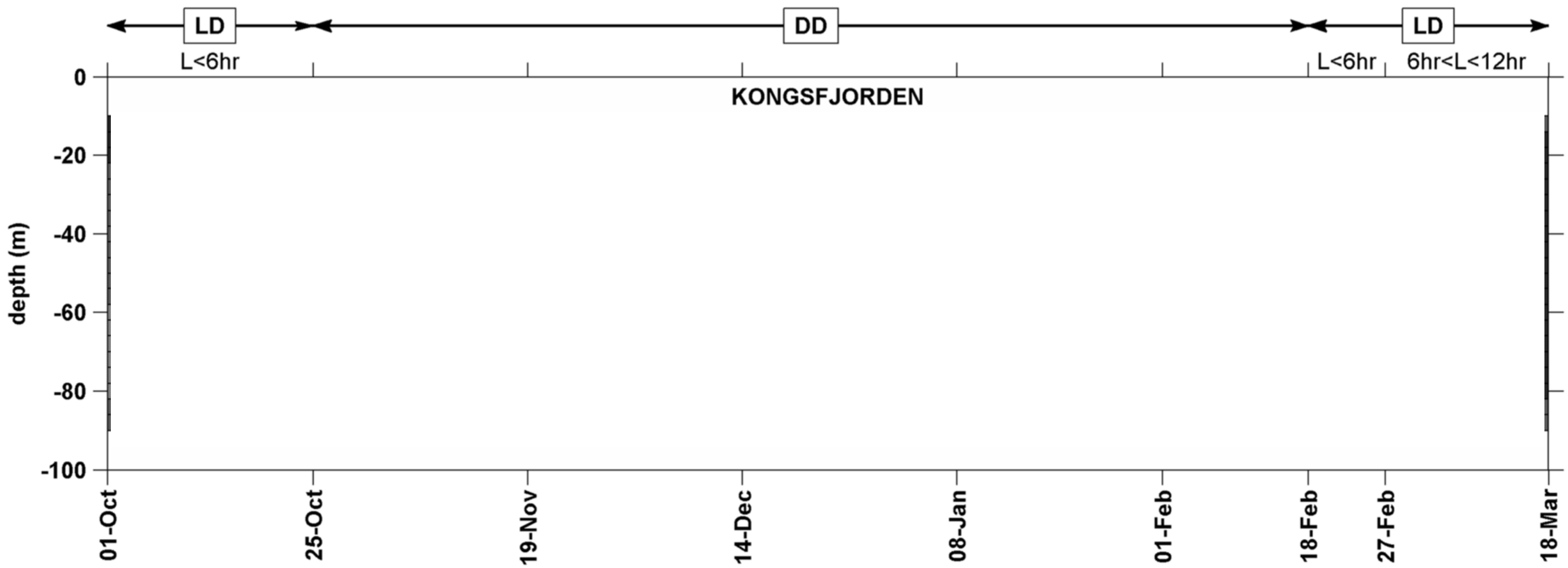
**Moonlight drives oceanic scale mass vertical migration of zooplankton during the Arctic winter.**

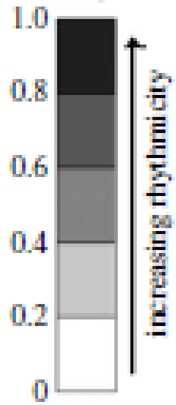
Kim Last &
Laura Hobbs




WereWolves

# DVM throughout the polar night – right?



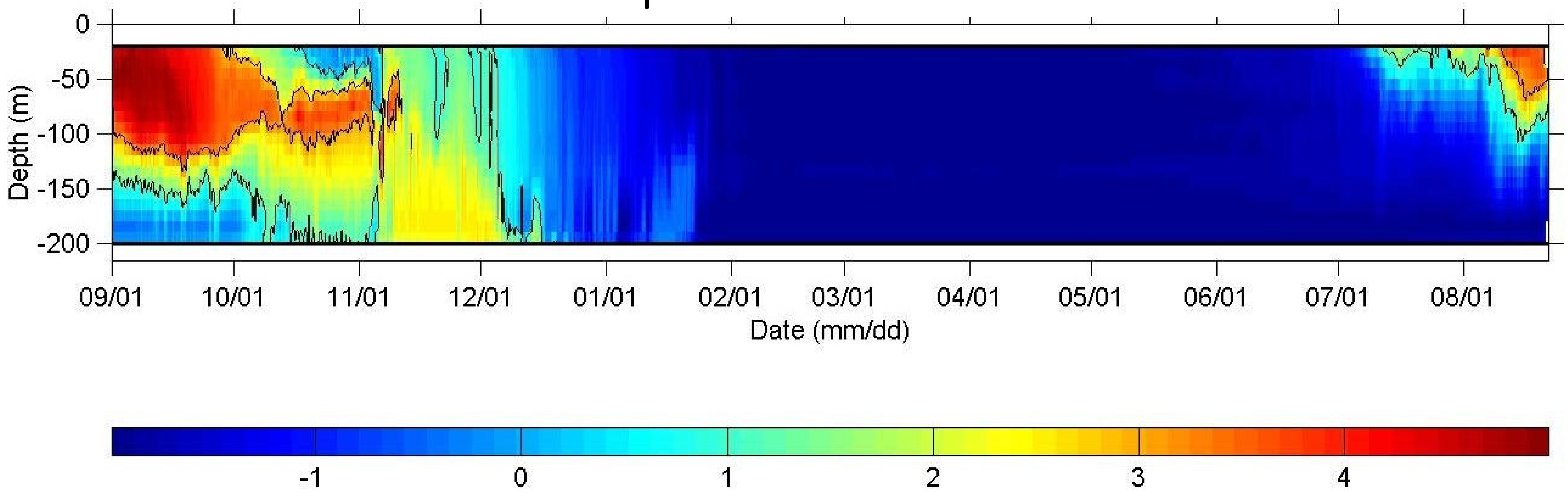

Generating a rhythmicity index for the circadian range

biology letters
Biol. Lett.
doi:10.1098/rsbl.2008.0484
Published online
Marine biology

**Diel vertical migration of Arctic zooplankton during the polar night**

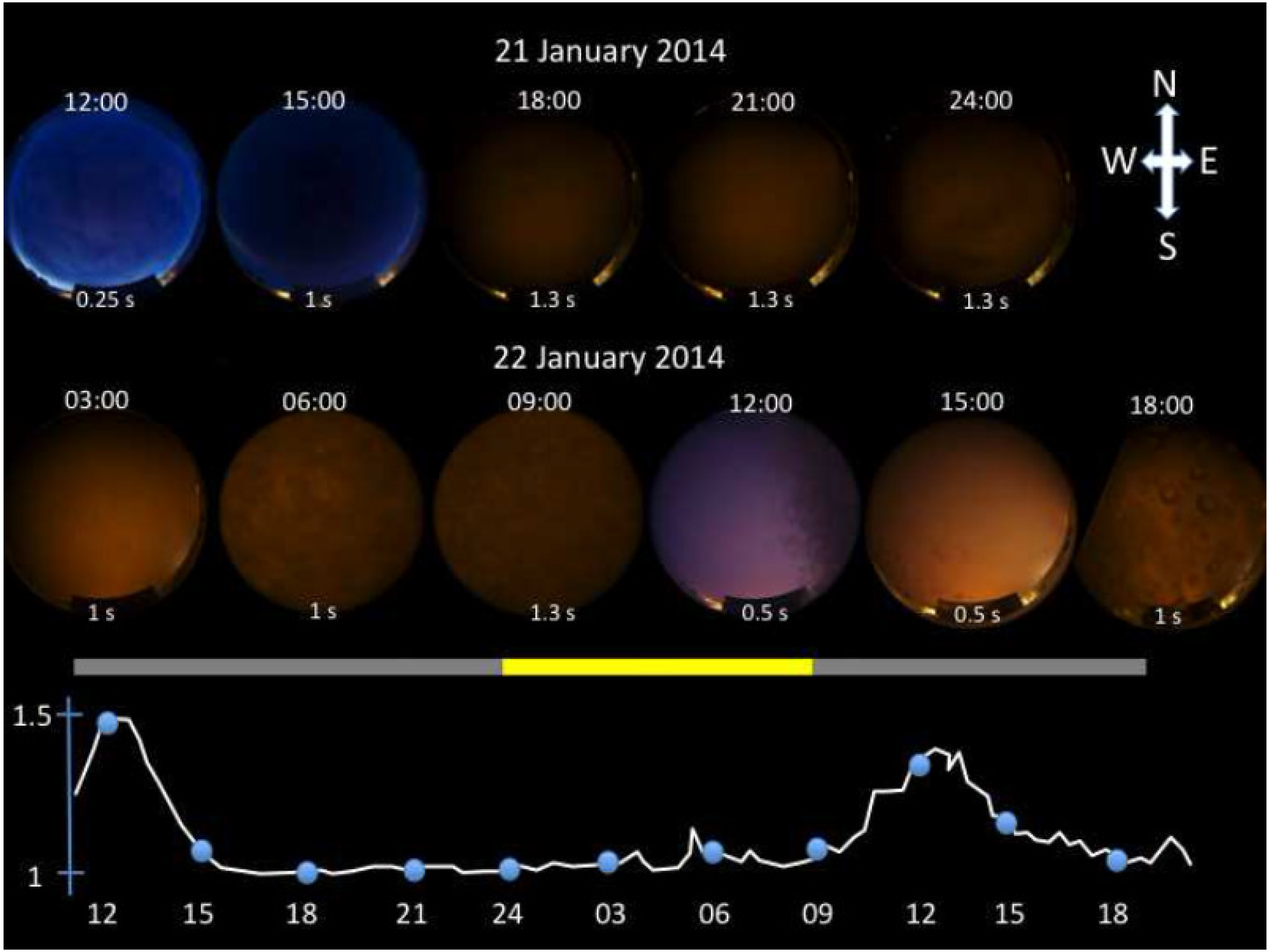
Jørgen Berge[1,2,*], Finlo Cottier[2], Kim S. Last[2], Øystein Varpe[1], Eva Leu[3], Janne Søreide[1], Ketil Eiane[4], Stig Falk-Petersen[3], Kate Willis[2], Henrik Nygård[1], Daniel Vogedes[1], Colin Griffiths[2], Geir Johnsen[1,5], Dag Lorentzen[1] and Andrew S. Brierley[6]

# Temperature Profile 2006/7



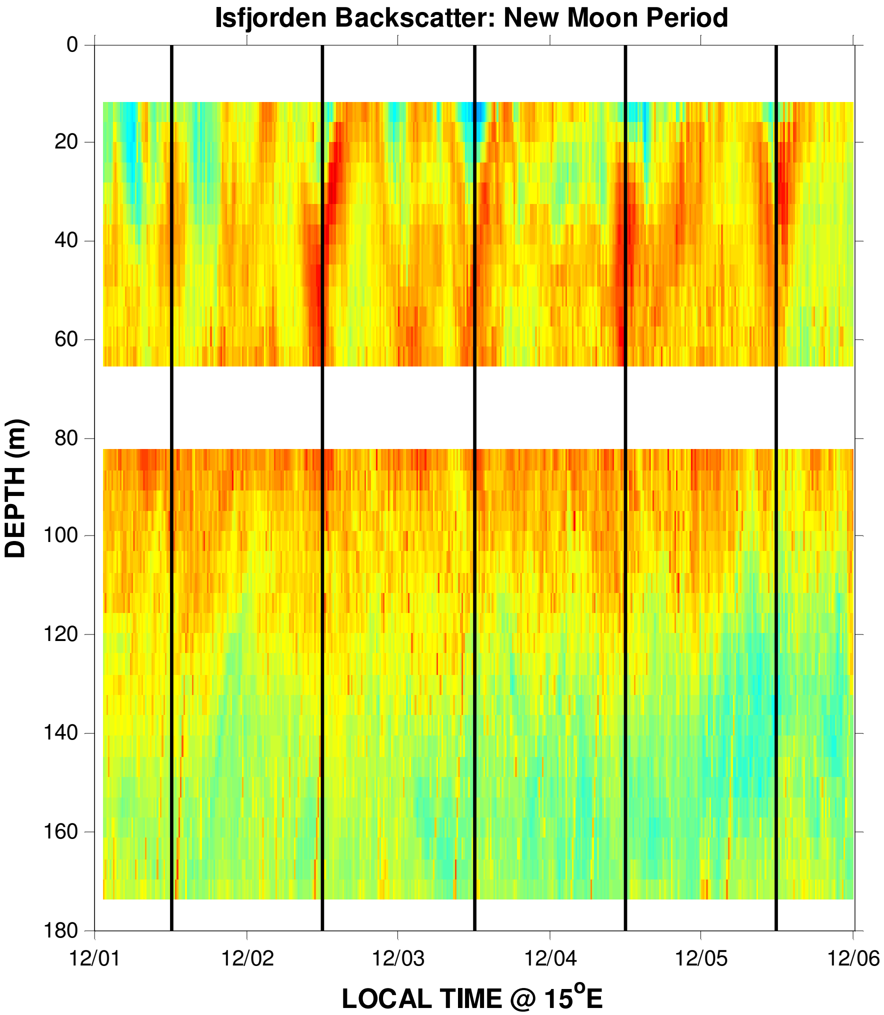

Berg et al 2008


Note: sunlight
… but no need for sun cream just yet
UNIS
M

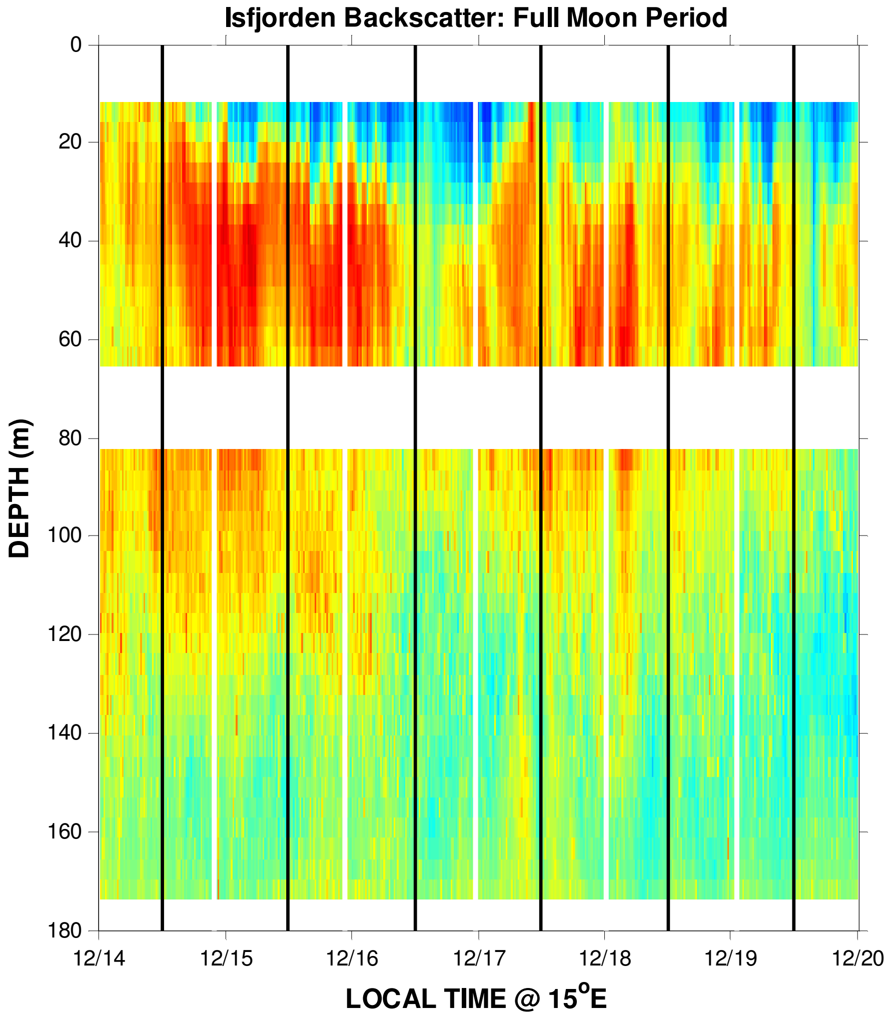



$10^{-7}$ µmol photons $m^{-2}$ $sec^{-1}$

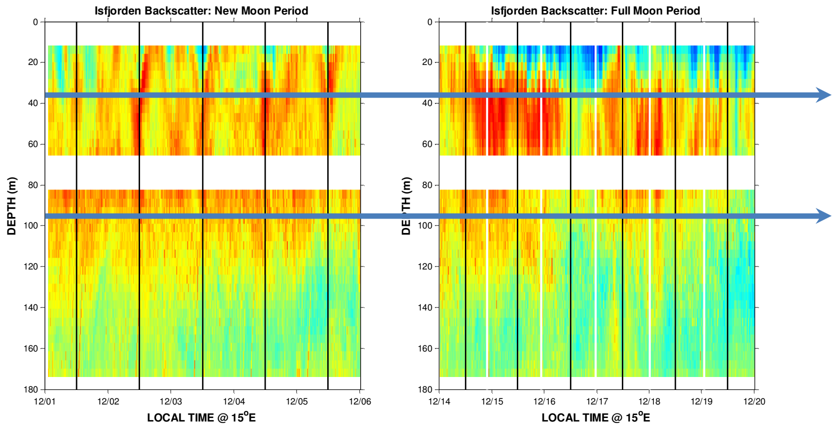
Cohen et al., 2015 PlosOne

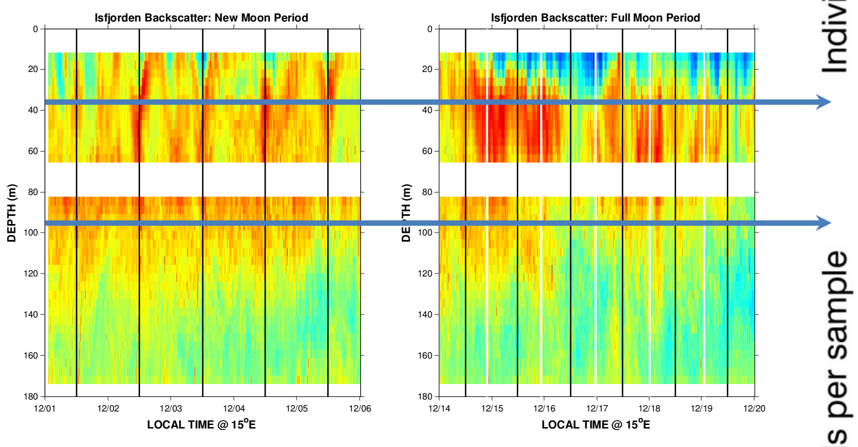


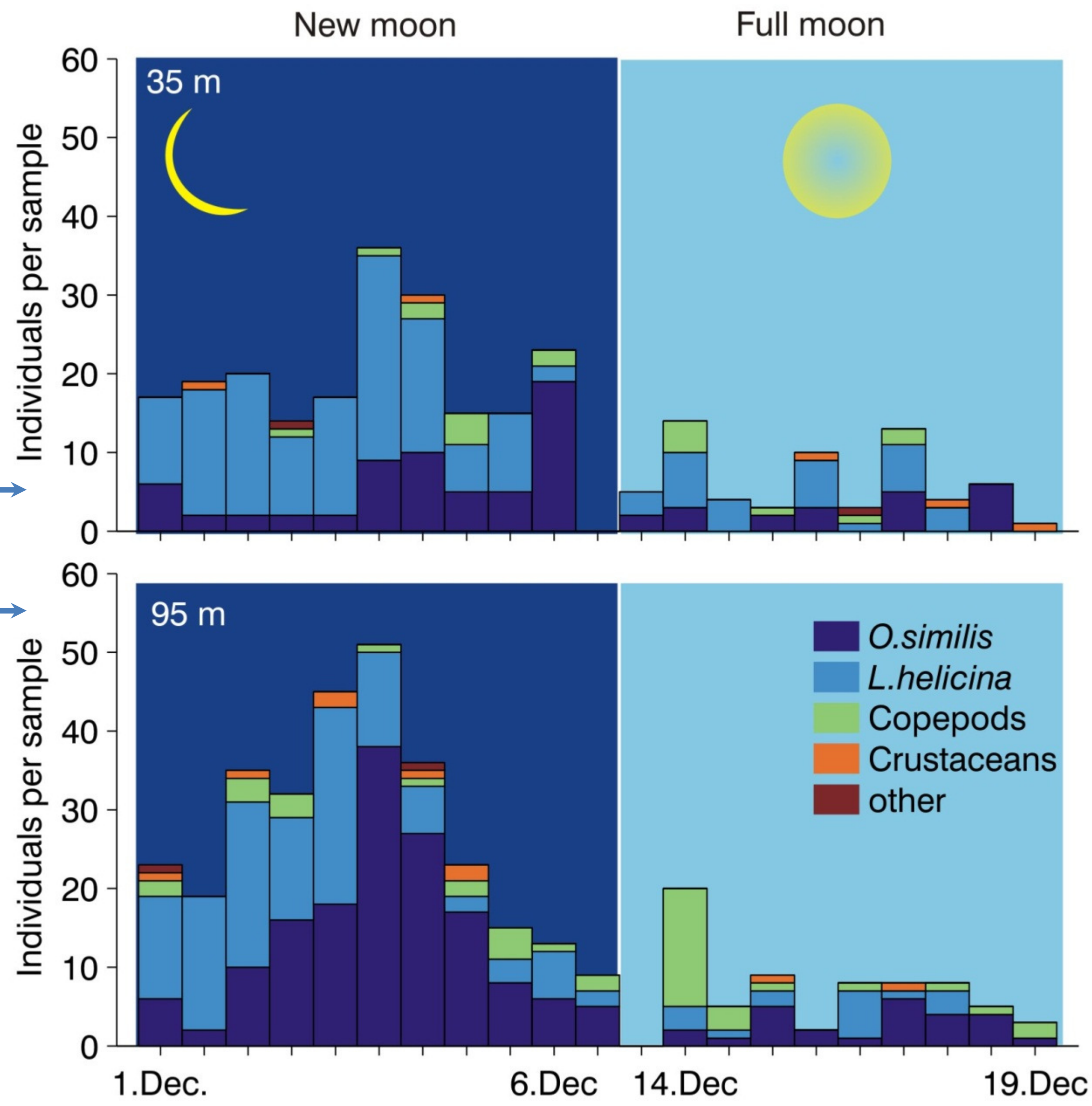
Isfjorden Backscatter: New Moon Period
DEPTH (m)
0
20
40
60
80
100
120
140
160
180
12/01
12/02
12/03
12/04
12/05
12/06
LOCAL TIME @ 15°E

Isfjorden Backscatter: Full Moon Period
DEPTH (m)
0
20
40
60
80
100
120
140
160
180
12/14
12/15
12/16
12/17
12/18
12/19
12/20
LOCAL TIME @ 15°E

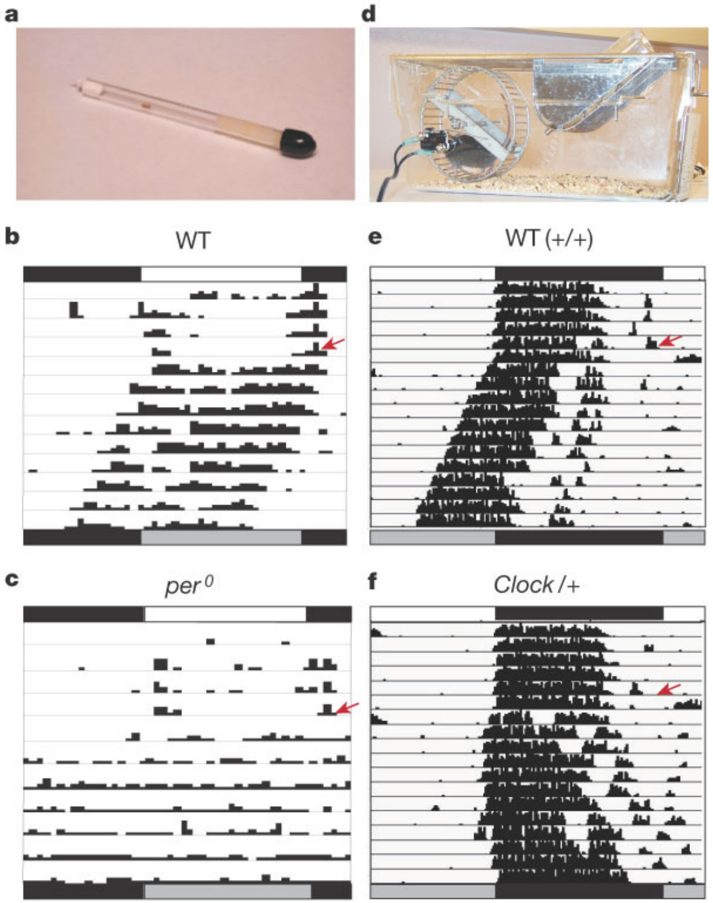

Isfjorden Backscatter: New Moon Period
Isfjorden Backscatter: Full Moon Period
DEPTH (m)
0
20
40
60
80
100
120
140
160
180
12/01
12/02
12/03
12/04
12/05
12/06
12/14
12/15
12/16
12/17
12/18
12/19
12/20
LOCAL TIME @ 15°E



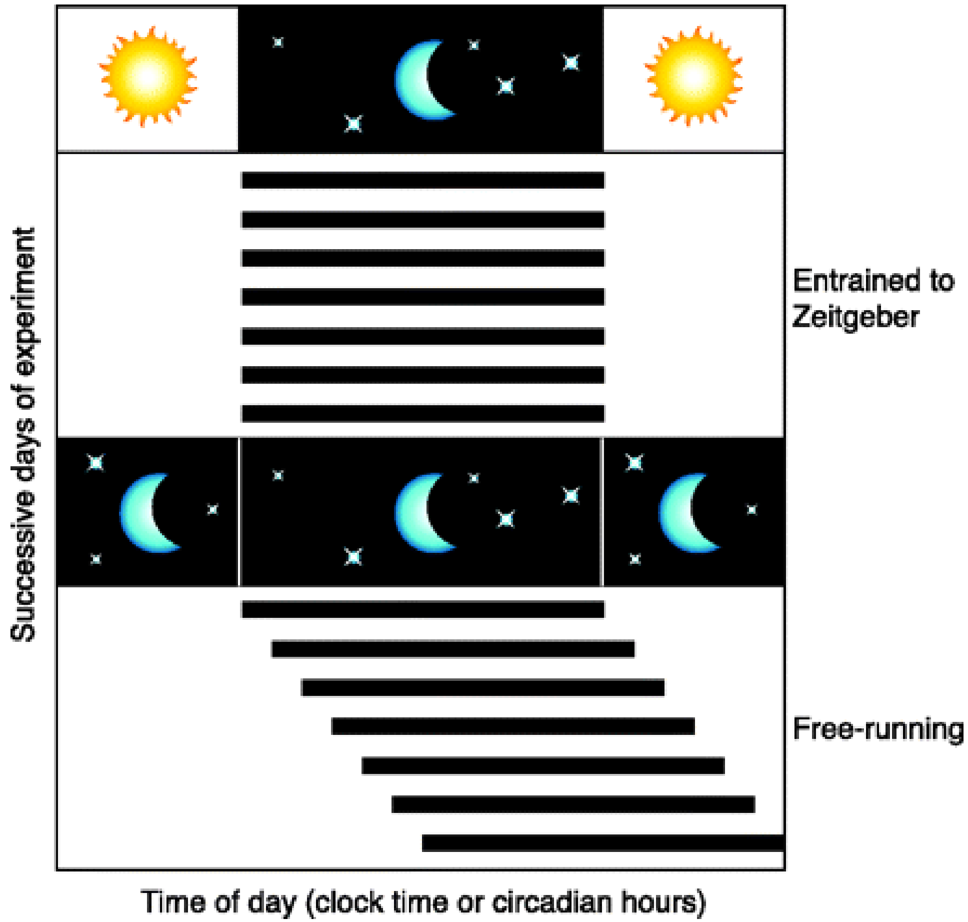




Oithona / Limacina dominate

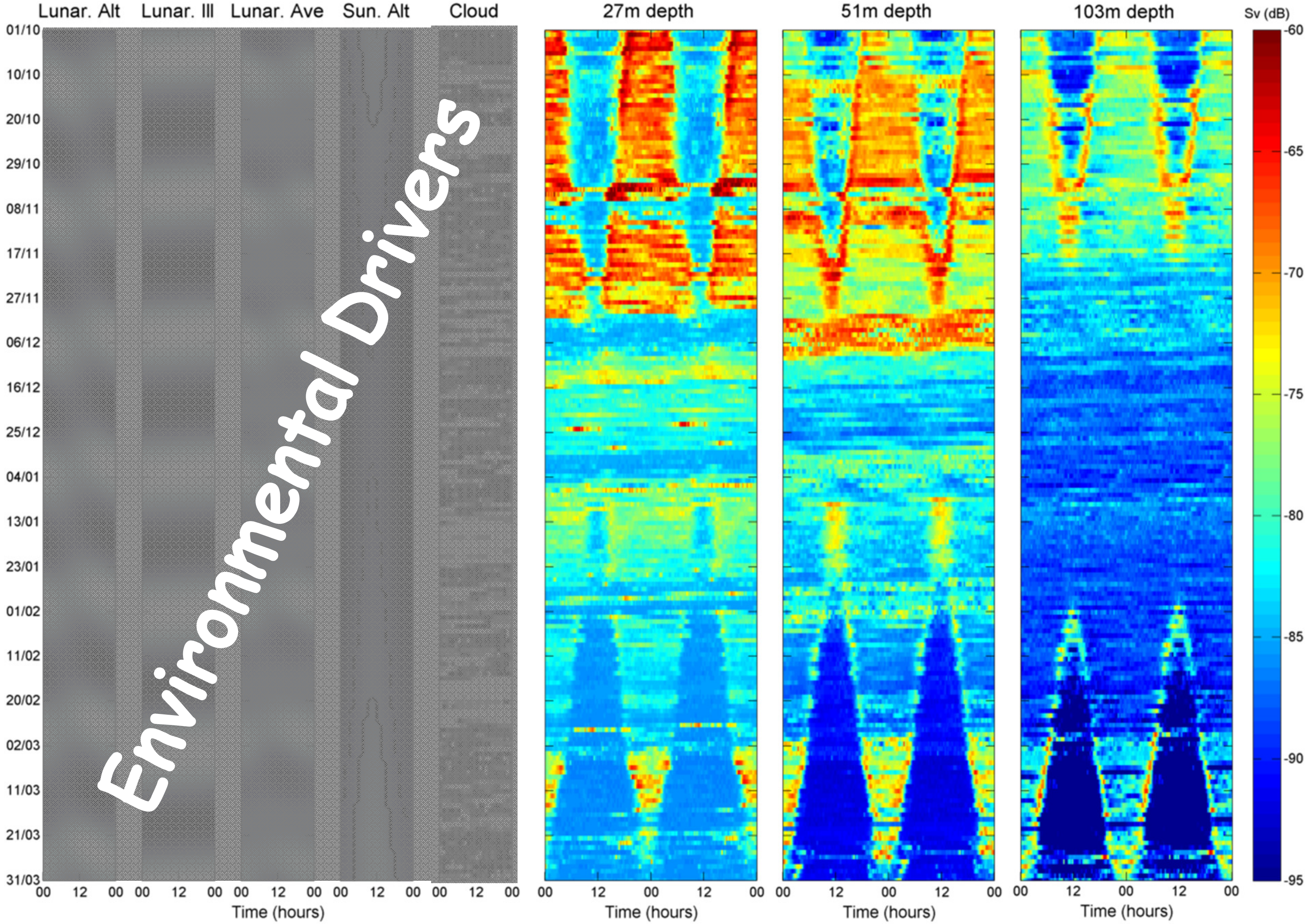
Data from Malin Daase




Circadian rhythms from flies to human
Panda et al., Nature 417, 329-335

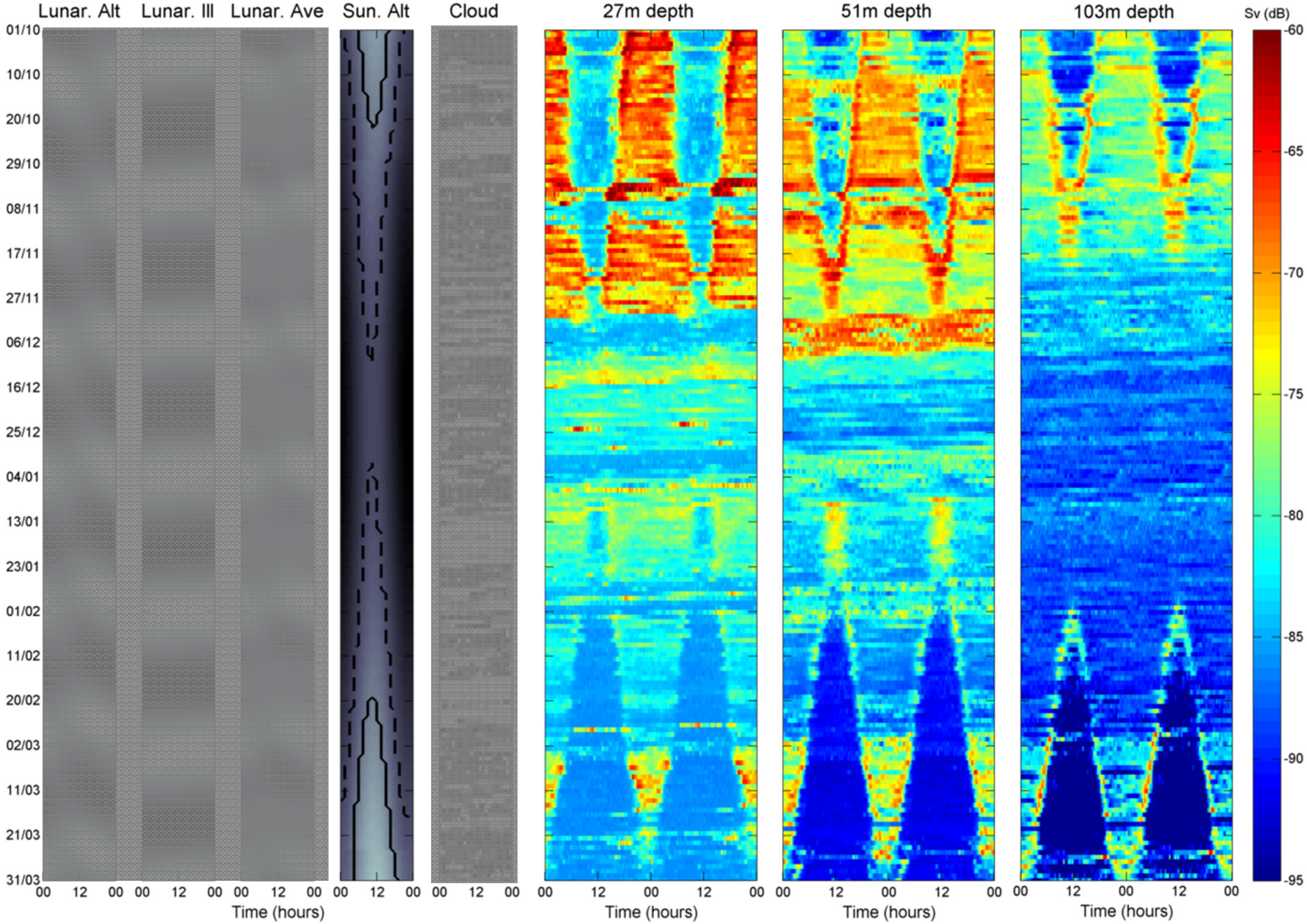


# 2006/07



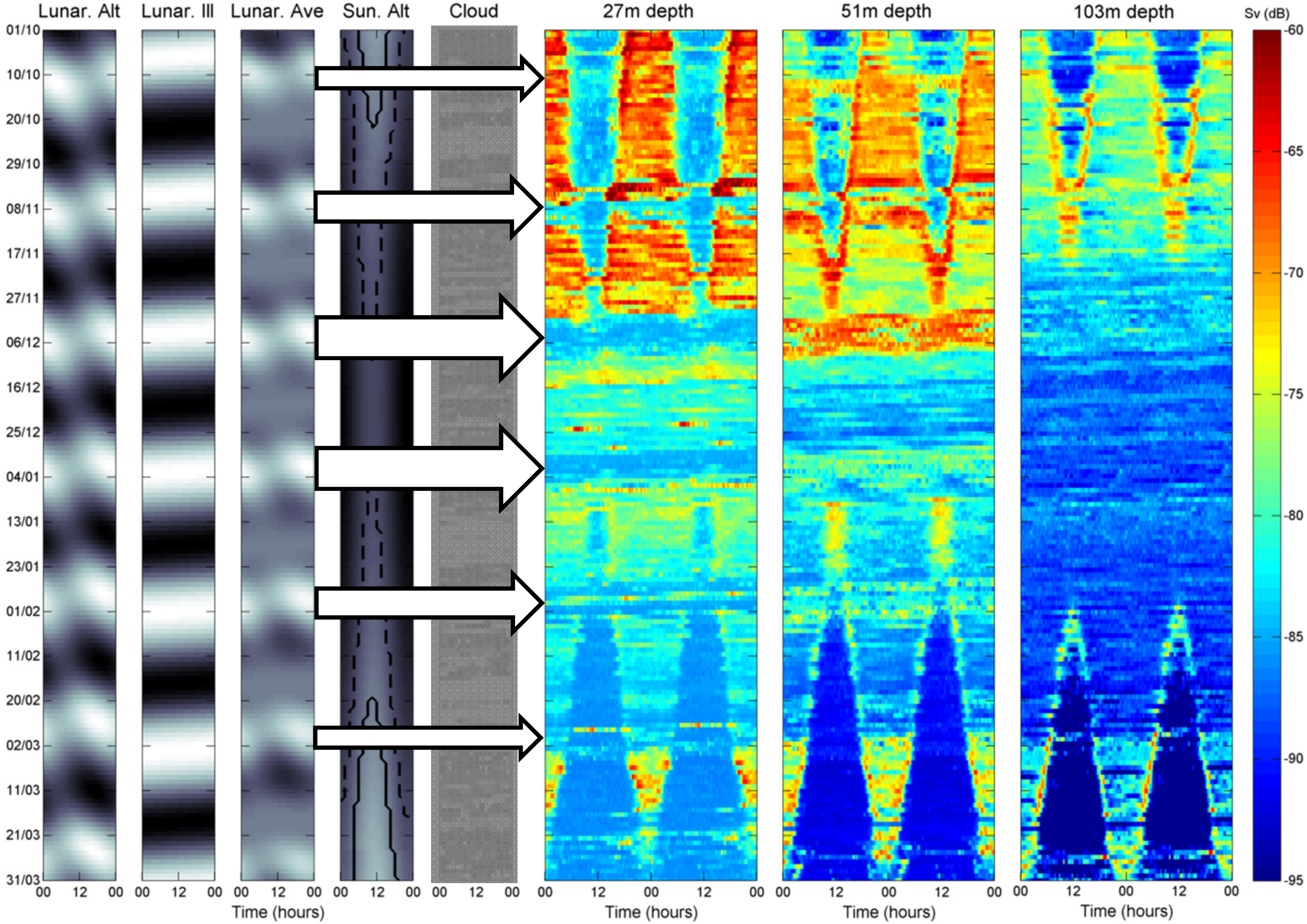
Lunar. Alt
Lunar. Ill
Lunar. Ave
Sun. Alt
Cloud
27m depth
51m depth
103m depth
Sv (dB)
-60
-65
-70
-75
-80
-85
-90
-95
01/10
10/10
20/10
29/10
08/11
17/11
27/11
06/12
16/12
25/12
04/01
13/01
23/01
01/02
11/02
20/02
02/03
11/03
21/03
31/03
00 12 00
Time (hours)
Environmental Drivers

# 2006/07

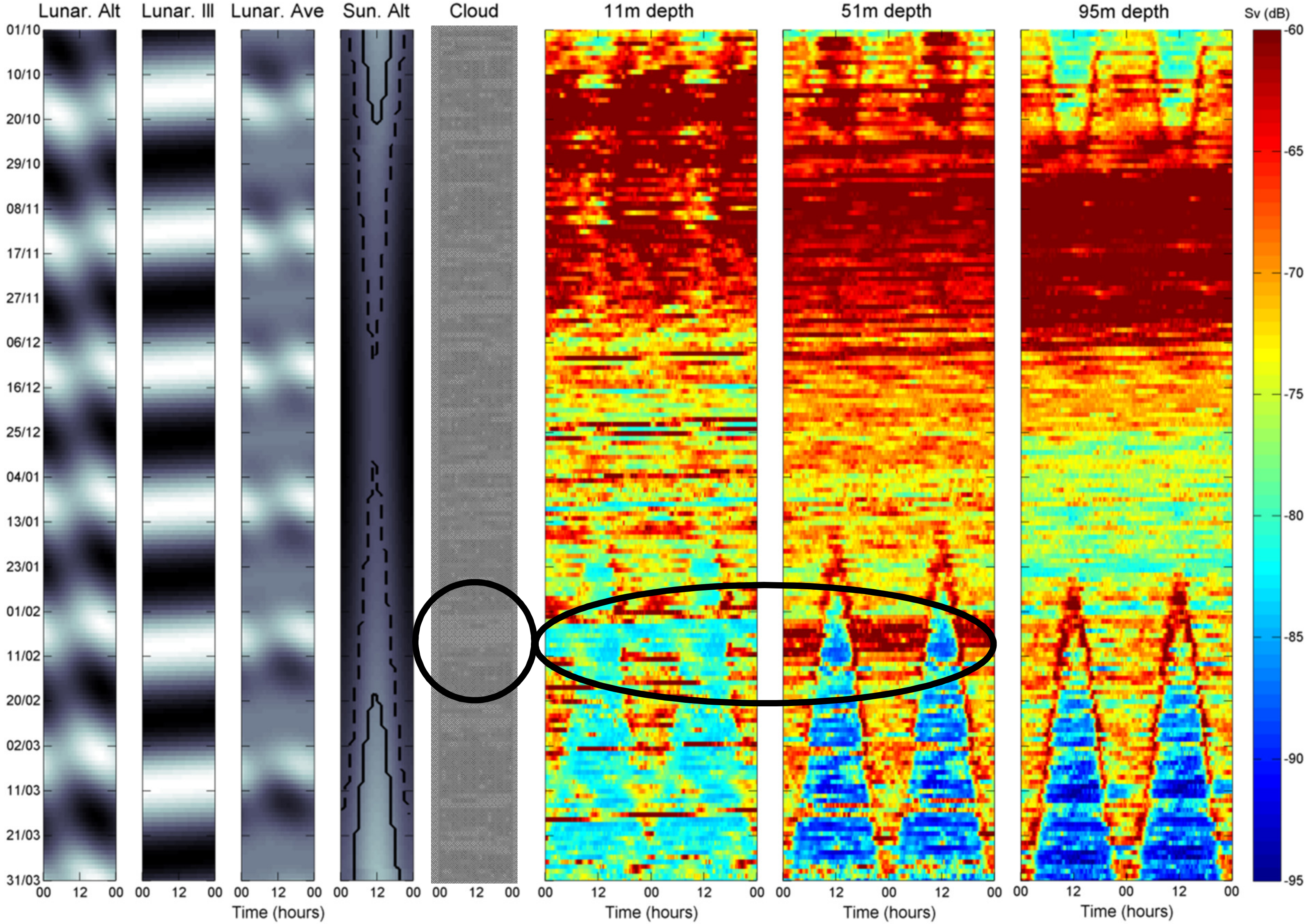


Lunar. Alt
Lunar. Ill
Lunar. Ave
Sun. Alt
Cloud
27m depth
51m depth
103m depth
Sv (dB)
-60
-65
-70
-75
-80
-85
-90
-95
01/10
10/10
20/10
29/10
08/11
17/11
27/11
06/12
16/12
25/12
04/01
13/01
23/01
01/02
11/02
20/02
02/03
11/03
21/03
31/03
00
12
Time (hours)

# 2006/07


Lunar. Alt
Lunar. Ill
Lunar. Ave
Sun. Alt
Cloud
27m depth
51m depth
103m depth
Sv (dB)
-60
-65
-70
-75
-80
-85
-90
-95
01/10
10/10
20/10
29/10
08/11
17/11
27/11
06/12
16/12
25/12
04/01
13/01
23/01
01/02
11/02
20/02
02/03
11/03
21/03
31/03
00
12
Time (hours)

# 2008/09



Lunar. Alt
Lunar. Ill
Lunar. Ave
Sun. Alt
Cloud
11m depth
51m depth
95m depth
Sv (dB)
-60
-65
-70
-75
-80
-85
-90
-95
01/10
10/10
20/10
29/10
08/11
17/11
27/11
06/12
16/12
25/12
04/01
13/01
23/01
01/02
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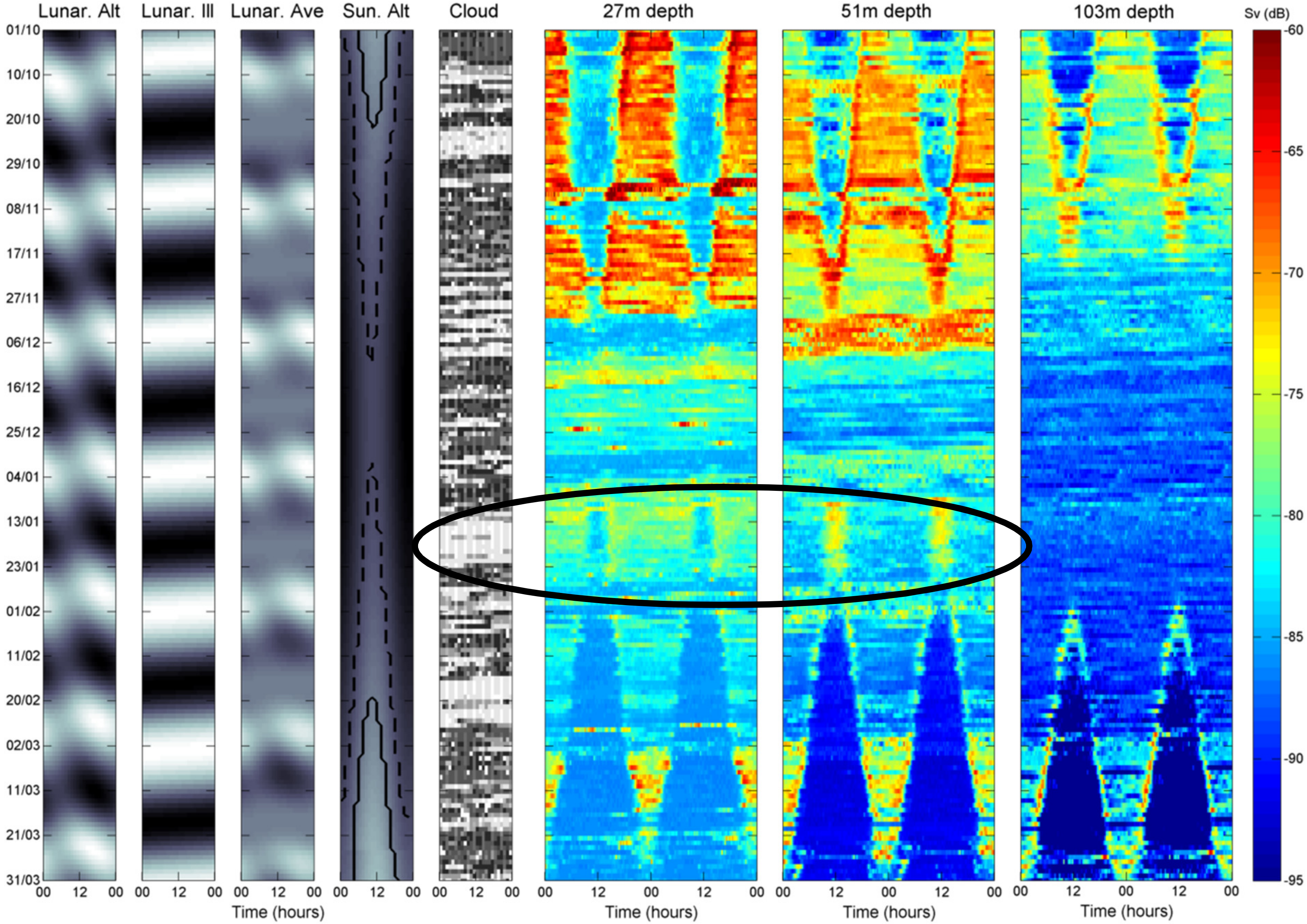
20/02
02/03
11/03
21/03
31/03
00 12 00
Time (hours)
00 12 00 12 00

# 2006/07



Lunar. Alt
Lunar. Ill
Lunar. Ave
Sun. Alt
Cloud
27m depth
51m depth
103m depth
Sv (dB)
01/10
10/10
20/10
29/10
08/11
17/11
27/11
06/12
16/12
25/12
04/01
13/01
23/01
01/02
11/02
20/02
02/03
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-65
-70
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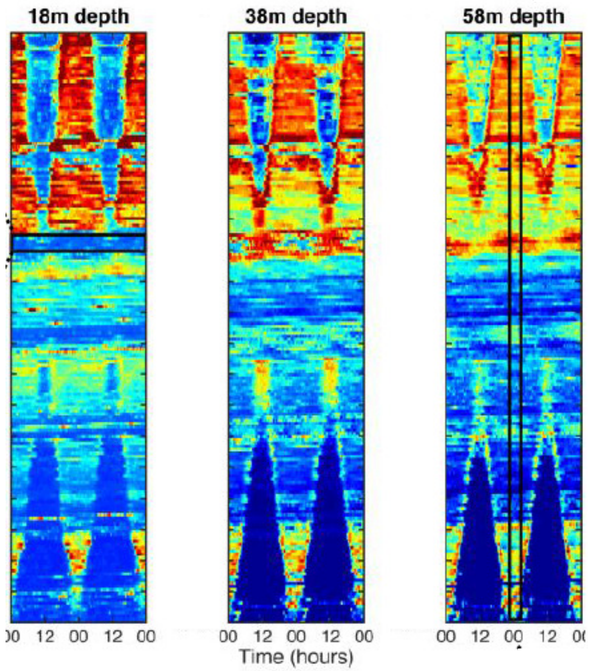
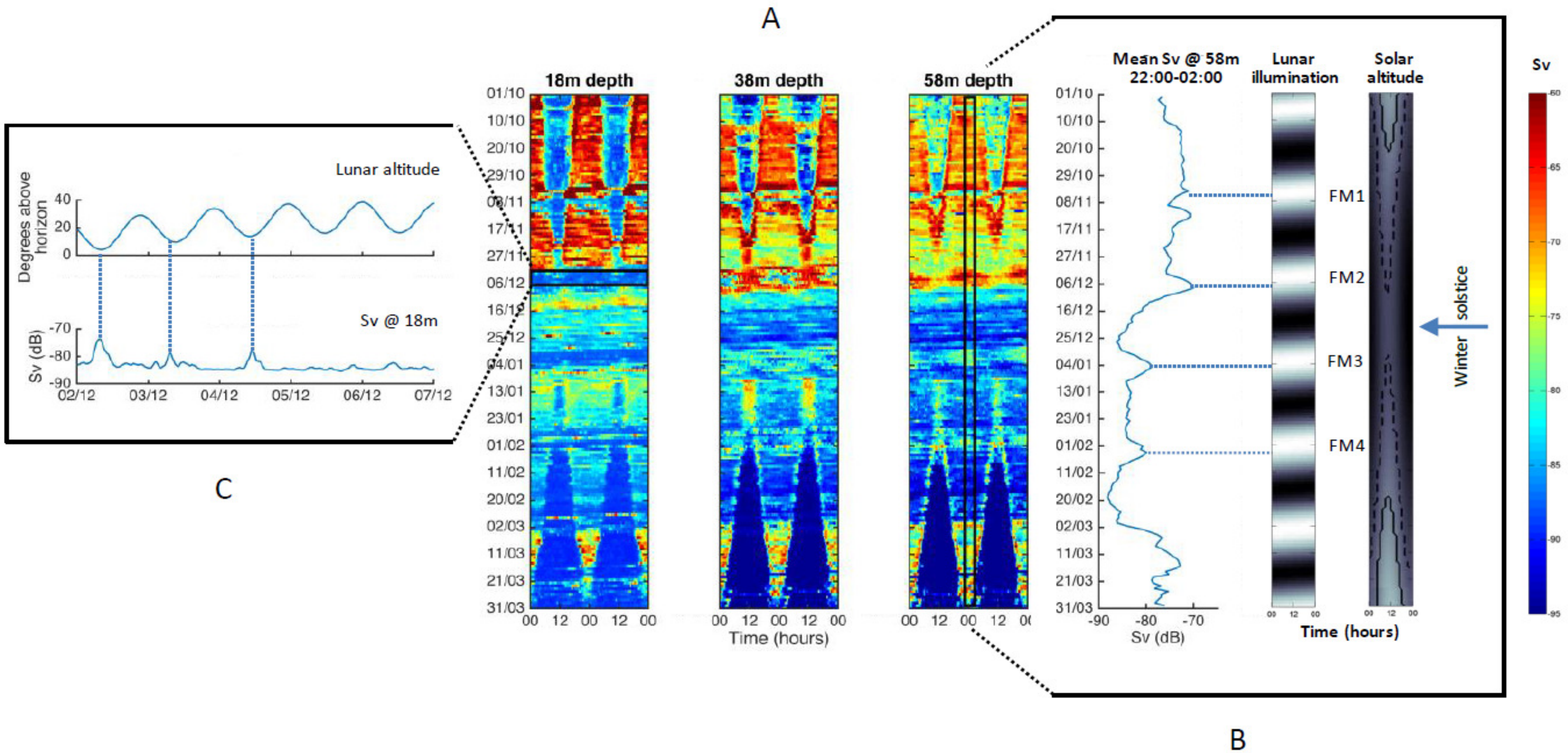
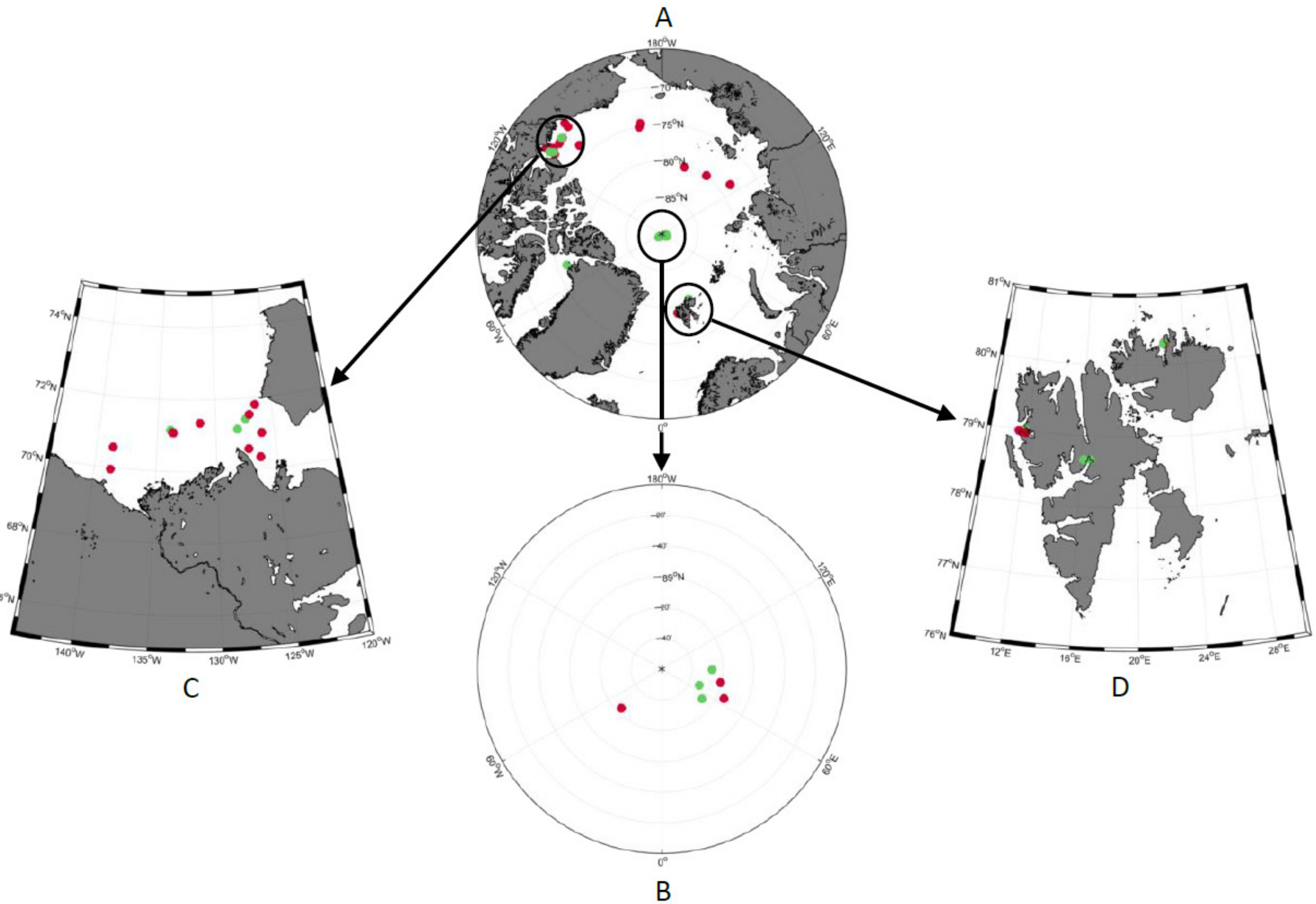
-80
-85
-90
-95
00
12
Time (hours)

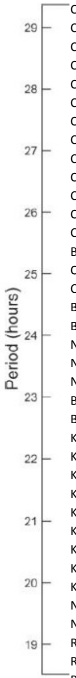
A



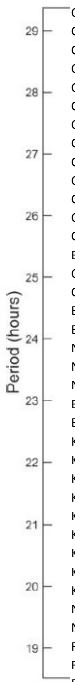
18m depth
38m depth
58m depth
00 12 00 12 00
00 12 00 12 00
00 12 00 12 00
Time (hours)


A
B
C
18m depth
38m depth
58m depth
Time (hours)
Mean Sv @ 58m 22:00-02:00
Lunar illumination
Solar altitude
Sv
FM1
FM2
FM3
FM4
Winter solstice
Time (hours)
Sv (dB)
Lunar altitude
Degrees above horizon
Sv @ 18m
Sv (dB)

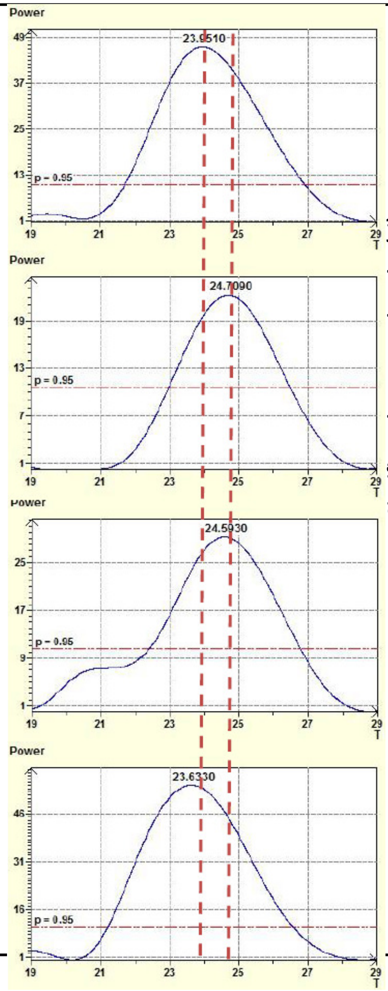

A
B
C
D

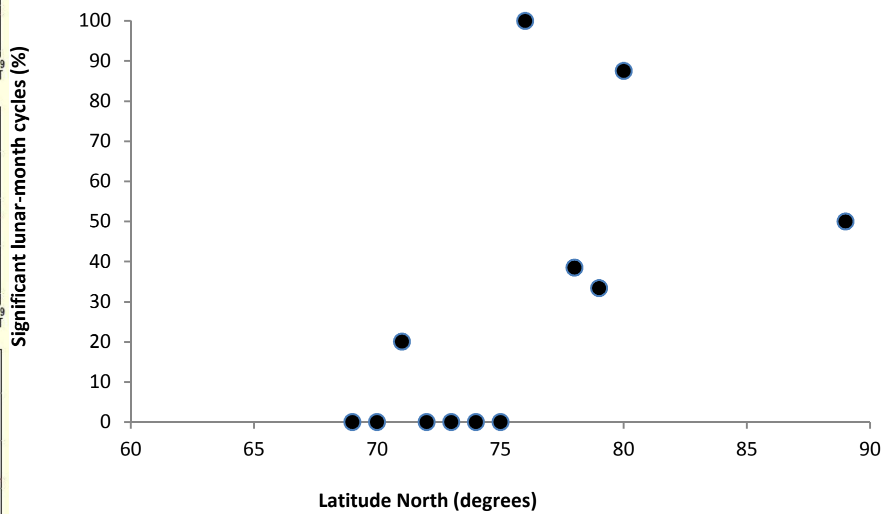



| ADCP | Lat. | Long. | FM1 | FM2 | FM3 | FM4 | 20 m | 40 m | 60 m |
|---|---|---|---|---|---|---|---|---|---|
| CA_03_04E | 69° 57.31' N | 138° 40.42' W | 25.006 | 19.852 | 23.273 | 23.962 | | | |
| CA_04_05D | 70° 20.36' N | 126° 21.42' W | 24.429 | 25.189 | 27.941 | 24.305 | | | |
| CA_03_04F | 70° 34.63' N | 138° 39.29' W | 23.951 | 24.709 | 24.593 | 23.633 | | | |
| CA_03_04C | 70° 35.32' N | 127° 16.23' W | 23.962 | 27.129 | 24.316 | 22.877 | | | |
| CA_05_06C | 71° 00.41' N | 126° 04.46' W | 23.532 | 24.019 | 23.648 | 24.045 | 29.5* | 29.5* | - |
| CA_05_06A | 71° 04.81' N | 133° 37.75' W | 24.770 | 24.061 | 25.991 | 23.512 | 29.115 | 25.707 | 25.575 |
| CA_04_05A | 71° 05.15' N | 133° 43.27' W | 23.765 | 25.409 | 24.692 | - | 29.5* | - | - |
| CA_03_04d | 71° 08.99' N | 133° 53.88' W | 24.670 | 26.139 | 23.873 | 23.377 | | | |
| CA_03_04A | 71° 09.18' N | 128° 07.57' W | 23.735 | 24.456 | - | 24.332 | | | |
| CA_03_04H | 71° 21.36' N | 131° 21.82' W | 23.447 | 24.262 | 19.777 | 22.573 | | | |
| CA_03_04B | 71° 25.23' N | 127° 22.50' W | 25.264 | - | 24.082 | 22.717 | | | |
| CA_03_04I | 71° 32.23' N | 127° 01.43' W | 23.879 | 22.403 | 24.354 | 23.205 | | | |
| CA_04_05C | 71° 32.27' N | 127° 01.46' W | 25.017 | 24.714 | - | 24.659 | - | 27.933 | 25.575 |
| CA_03_04J | 71° 47.89' N | 126° 27.35' W | 23.899 | 28.336 | 24.066 | 23.873 | | | |
| BE_02_04A | 73° 27.87' N | 136° 59.82' W | 22.005 | 24.130 | 23.941 | 23.925 | | | |
| CH_06_08A | 74° 38.68' N | 168° 47.76' W | 23.694 | 24.024 | - | 25.480 | | | |
| CH_05_07A | 75° 06.00' N | 167° 59.91' W | 23.786 | 22.321 | 21.625 | 24.009 | | | |
| BB_97_99B | 76° 17.38' N | 071° 56.37' W | 24.072 | 23.842 | 24.339 | 24.045 | 26.525 | - | 29.5* |
| BB_98_99B | 76° 17.60' N | 071° 55.63' W | 23.589 | 23.663 | 25.474 | 23.719 | 29.5* | - | - |
| NB_04_05A | 78° 25.84' N | 125° 36.61' E | 23.988 | - | 23.977 | - | | | |
| NB_06_07A | 78° 25.94' N | 125° 43.42' E | 24.284 | - | 22.191 | 27.176 | | | |
| NB_05_06A | 78° 27.99' N | 125° 40.91' E | 24.898 | 22.005 | 21.176 | 23.806 | 29.5* | 29.5* | 29.5* |
| BF_08_09A | 78° 39.76' N | 016° 11.25' E | 26.800 | 22.545 | - | 22.036 | 29.5* | - | 29.5* |
| BF_10_11A | 78° 39.80' N | 016° 41.50' E | 22.731 | 28.019 | 24.697 | 24.505 | | | |
| KF_04_05A | 78° 57.44' N | 011° 49.36' E | 24.764 | 25.148 | 27.365 | 25.991 | | | |
| KF_07_08A | 78° 57.44' N | 011° 49.60' E | 26.383 | 25.456 | 21.469 | - | - | 26.667 | 27.584 |
| KF_12_13A | 78° 57.73' N | 011° 48.43' E | 23.750 | 21.063 | 19.239 | - | | | |
| KF_09_10A | 78° 57.75' N | 011° 45.55' E | 23.879 | 20.135 | 26.427 | 24.402 | - | 27.473 | - |
| KF_10_11A | 78° 57.75' N | 011° 45.56' E | 24.268 | 26.232 | - | - | 29.5* | 29.5* | 29.5* |
| KF_11_12A | 78° 57.75' N | 011° 45.56' E | 26.845 | 26.497 | 24.960 | 19.152 | 29.5* | 29.5* | - |
| KF_13_14A | 78° 57.75' N | 011° 48.30' E | 21.160 | 21.672 | 28.351 | 24.183 | | | |
| KF_08_09A | 78° 59.18' N | 011° 20.93' E | - | 28.870 | 26.370 | 23.998 | 33.784 | 29.5* | 29.5* |
| KF_06_07A | 79° 01.20' N | 011° 46.42' E | 23.636 | 24.003 | 25.640 | 26.606 | 26.596 | 29.5* | 29.5* |
| NB_04_05B | 79° 55.10' N | 142° 21.15' E | 24.056 | 21.779 | 19.219 | 28.242 | 26.240 | 27.248 | 33.333 |
| NB_05_06B | 79° 55.72' N | 142° 21.81' E | - | 20.943 | - | 25.551 | | | |
| RF_07_08A | 80° 16.89' N | 022° 18.90' E | 23.704 | 26.878 | 26.395 | 22.439 | - | 29.5* | 29.5* |
| RF_09_10A | 80° 17.03' N | 022° 18.15' E | 23.573 | 26.288 | 19.003 | - | 29.5* | 29.5* | 26.042 |
| RF_10_11A | 80° 17.22' N | 022° 15.45' E | 24.114 | 25.345 | 24.391 | 25.000 | 29.5* | 30.581 | - |
| RF_06_07A | 80° 17.60' N | 022° 18.80' E | 24.040 | 24.994 | 23.941 | 24.204 | 29.5* | - | 29.5* |
| RF_11_12A | 80° 18.01' N | 022° 17.66' E | 25.574 | 24.273 | 25.339 | 21.299 | 29.5* | 29.5* | 29.5* |
| RF_13_14A | 80° 18.08' N | 022° 17.44' E | 22.638 | 21.887 | 21.481 | 24.543 | 29.5* | - | 32.787 |
| RF_12_13A | 80° 18.42' N | 022° 17.50' E | 23.704 | 26.484 | - | 21.423 | 29.5* | 29.5* | - |
| NB_07_08A | 80° 20.93' N | 161° 15.84' E | 23.899 | 27.003 | 24.648 | 19.556 | | | |
| NP_05_06A | 89° 15.17' N | 064° 41.51' E | 25.646 | 20.800 | 25.143 | - | - | 29.5* | - |
| NP_06_08A | 89° 20.81' N | 077° 07.21' E | 19.192 | - | 26.599 | - | - | 34.483 | - |
| NP_03_04A | 89° 23.34' N | 046° 01.15' W | 28.235 | 24.284 | 23.837 | 19.003 | | - | 26.882 |
| NP_04_05A | 89° 27.29' N | 089° 19.74' E | - | 25.023 | 23.858 | - | 29.5* | 29.5* | 26.624 |
| NP_02_03A | 89° 27.46' N | 053° 31.26' E | 19.347 | 23.482 | 25.856 | 26.541 | - | 31.056 | 29.5* |
| NP_01_02A | 89° 33.41' N | 066° 38.82' E | 25.439 | - | 26.232 | 22.040 | 28.409 | 26.178 | - |




| ADCP | Lat. | Long. | FM1 | FM4 | 20 m | 40 m | 60 m |
|---|---|---|---|---|---|---|---|
| CA_03_04E | 69° 57.31' N | 138° 40.42' W | *25.006* | *23.962* | | | |
| CA_04_05D | 70° 20.36' N | 126° 21.42' W | *24.429* | *24.305* | | | |
| CA_03_04F | 70° 34.63' N | 138° 39.29' W | *23.951* | *23.633* | | | |
| CA_03_04C | 70° 35.32' N | 127° 16.23' W | *23.962* | *22.877* | | | |
| CA_05_06C | 71° 00.41' N | 126° 04.46' W | *23.532* | | | | |
| CA_05_06A | 71° 04.81' N | 133° 37.75' W | *24.770* | | | | |
| CA_04_05A | 71° 05.15' N | 133° 43.27' W | *23.765* | | | | |
| CA_03_04d | 71° 08.99' N | 133° 53.88' W | *24.670* | | | | |
| CA_03_04A | 71° 09.18' N | 128° 07.57' W | *23.735* | | | | |
| CA_03_04H | 71° 21.36' N | 131° 21.82' W | *23.447* | | | | |
| CA_03_04B | 71° 25.23' N | 127° 22.50' W | *25.264* | | | | |
| CA_03_04I | 71° 32.23' N | 127° 01.43' W | *23.879* | | | | |
| CA_04_05C | 71° 32.27' N | 127° 01.46' W | *25.017* | | | | |
| CA_03_04J | 71° 47.89' N | 126° 27.35' W | *23.899* | | | | |
| BE_02_04A | 73° 27.87' N | 136° 59.82' W | *22.005* | | | | |
| CH_06_08A | 74° 38.68' N | 168° 47.76' W | *23.694* | | | | |
| CH_05_07A | 75° 06.00' N | 167° 59.91' W | *23.786* | | | | |
| BB_97_99B | 76° 17.38' N | 071° 56.37' W | *24.072* | | | | |
| BB_98_99B | 76° 17.60' N | 071° 55.63' W | *23.589* | | | | |
| NB_04_05A | 78° 25.84' N | 125° 36.61' E | *23.988* | | | | |
| NB_06_07A | 78° 25.94' N | 125° 43.42' E | *24.284* | | | | |
| NB_05_06A | 78° 27.99' N | 125° 40.91' E | 24.898 | | | | |
| BF_08_09A | 78° 39.76' N | 016° 11.25' E | *26.800* | | | | |
| BF_10_11A | 78° 39.80' N | 016° 41.50' E | *22.731* | | | | |
| KF_04_05A | 78° 57.44' N | 011° 49.36' E | *24.764* | | | | |
| KF_07_08A | 78° 57.44' N | 011° 49.60' E | *26.383* | | | | |
| KF_12_13A | 78° 57.73' N | 011° 48.43' E | *23.750* | | | | |
| KF_09_10A | 78° 57.75' N | 011° 45.55' E | *23.879* | | | | |
| KF_10_11A | 78° 57.75' N | 011° 45.56' E | *24.268* | | | | |
| KF_11_12A | 78° 57.75' N | 011° 45.56' E | *26.845* | | | | |
| KF_13_14A | 78° 57.75' N | 011° 48.30' E | *21.160* | | | | |
| KF_08_09A | 78° 59.18' N | 011° 20.93' E | - | | | | |
| KF_06_07A | 79° 01.20' N | 011° 46.42' E | *23.636* | | | | |
| NB_04_05B | 79° 55.10' N | 142° 21.15' E | *24.056* | | | | |
| NB_05_06B | 79° 55.72' N | 142° 21.81' E | - | | | | |
| RF_07_08A | 80° 16.89' N | 022° 18.90' E | *23.704* | | | | |
| RF_09_10A | 80° 17.03' N | 022° 18.15' E | *23.573* | - | *29.5** | *29.5** | *26.042* |
| RF_10_11A | 80° 17.22' N | 022° 15.45' E | *24.114* | *25.000* | *29.5** | *30.581* | - |
| RF_06_07A | 80° 17.60' N | 022° 18.80' E | *24.040* | 24.204 | *29.5** | - | *29.5** |
| RF_11_12A | 80° 18.01' N | 022° 17.66' E | *25.574* | *21.299* | *29.5** | *29.5** | *29.5** |
| RF_13_14A | 80° 18.08' N | 022° 17.44' E | *22.638* | *24.543* | *29.5** | - | *32.787* |
| RF_12_13A | 80° 18.42' N | 022° 17.50' E | *23.704* | 21.423 | *29.5** | *29.5** | - |
| NB_07_08A | 80° 20.93' N | 161° 15.84' E | *23.899* | 19.556 | | | |
| NP_05_06A | 89° 15.17' N | 064° 41.51' E | 25.646 | - | - | *29.5** | - |
| NP_06_08A | 89° 20.81' N | 077° 07.21' E | 19.192 | - | - | *34.483* | - |
| NP_03_04A | 89° 23.34' N | 046° 01.15' W | 28.235 | 19.003 | - | - | *26.882* |
| NP_04_05A | 89° 27.29' N | 089° 19.74' E | - | - | *29.5** | *29.5** | 26.624 |
| NP_02_03A | 89° 27.46' N | 053° 31.26' E | 19.347 | 26.541 | - | 31.056 | *29.5** |
| NP_01_02A | 89° 33.41' N | 066° 38.82' E | 25.439 | 22.040 | 28.409 | *26.178* | - |



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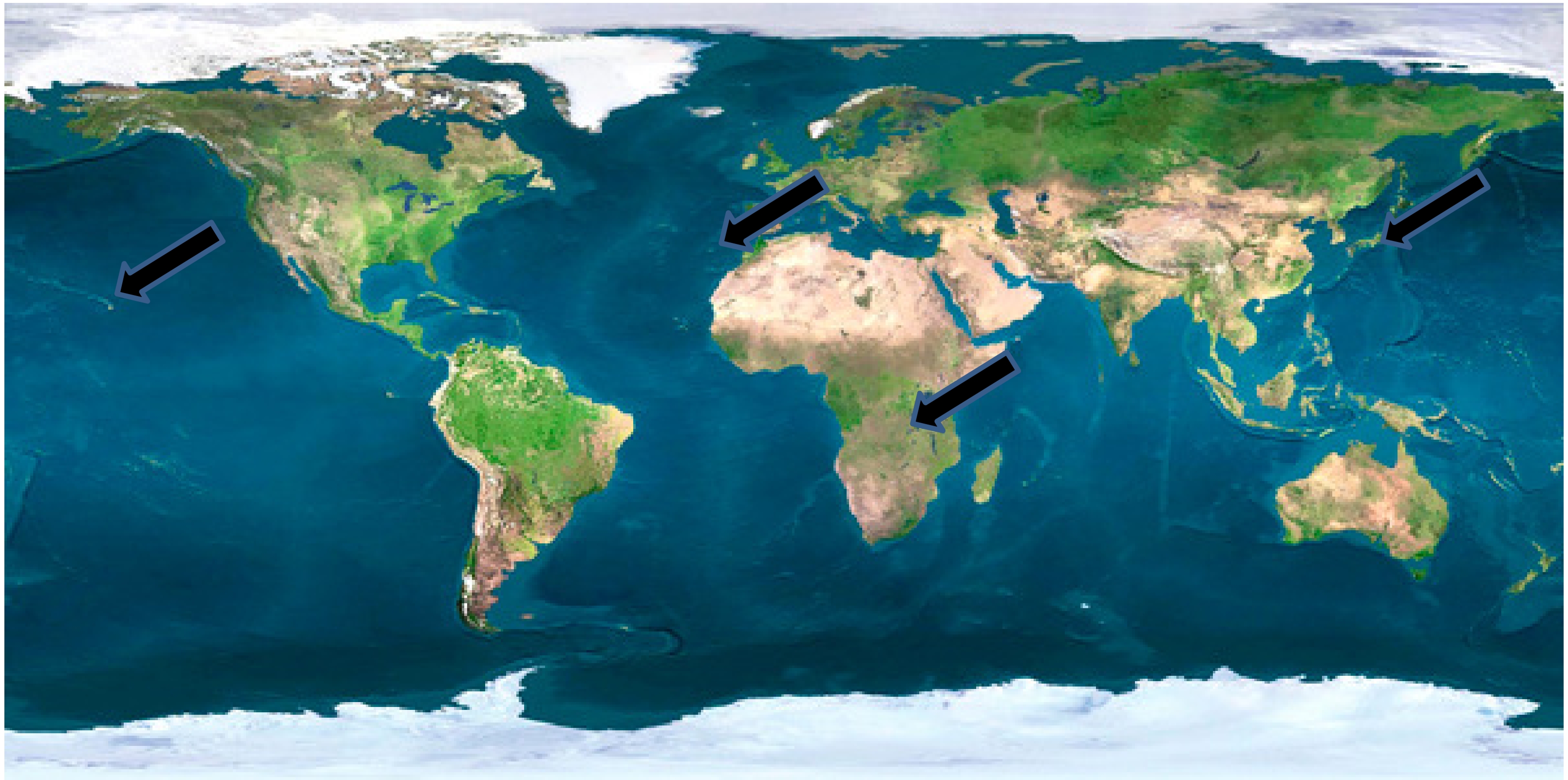

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Benoit-Bird et al 2009 found daily changes in backscatter as a consequence of lunar phase (no mention of lunar altitude).

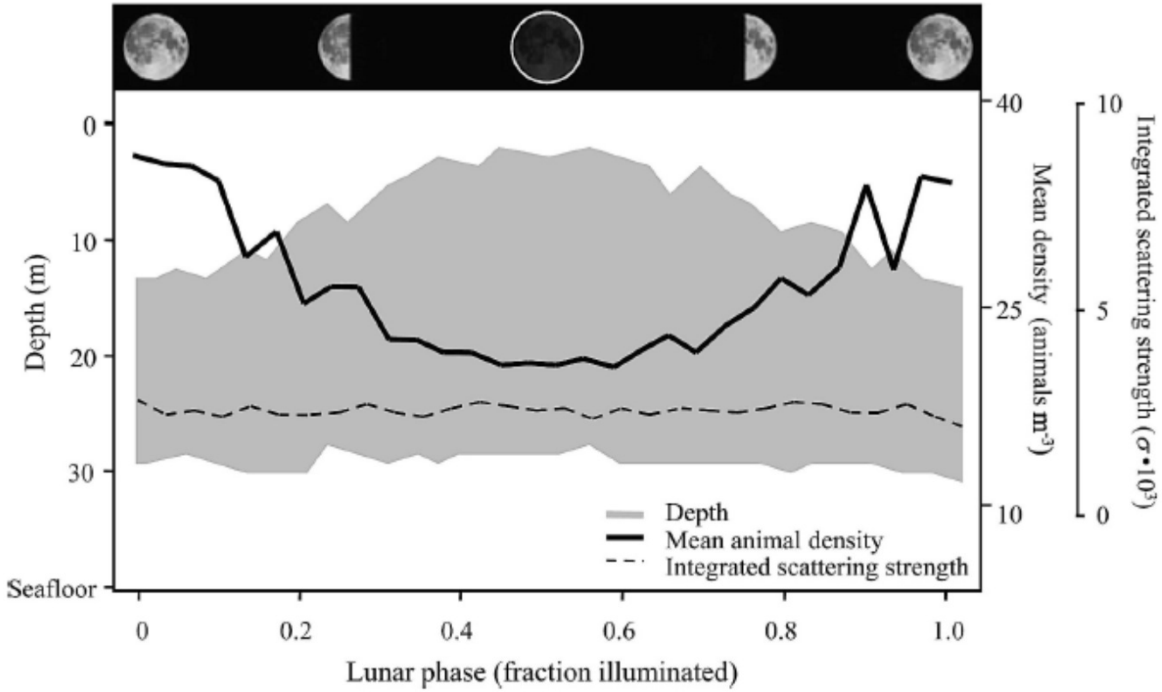



Fig. 7. An example from the 40-m mooring during the 2006 study showing layer depth, area scattering, and mean animal density as a function of lunar phase. A multiple linear regression on the full data set showed that layer minimum depth, thickness, and density were significantly affected by lunar phase, whereas layer maximum depth and area scattering, a measure of the total number of animals, were not.

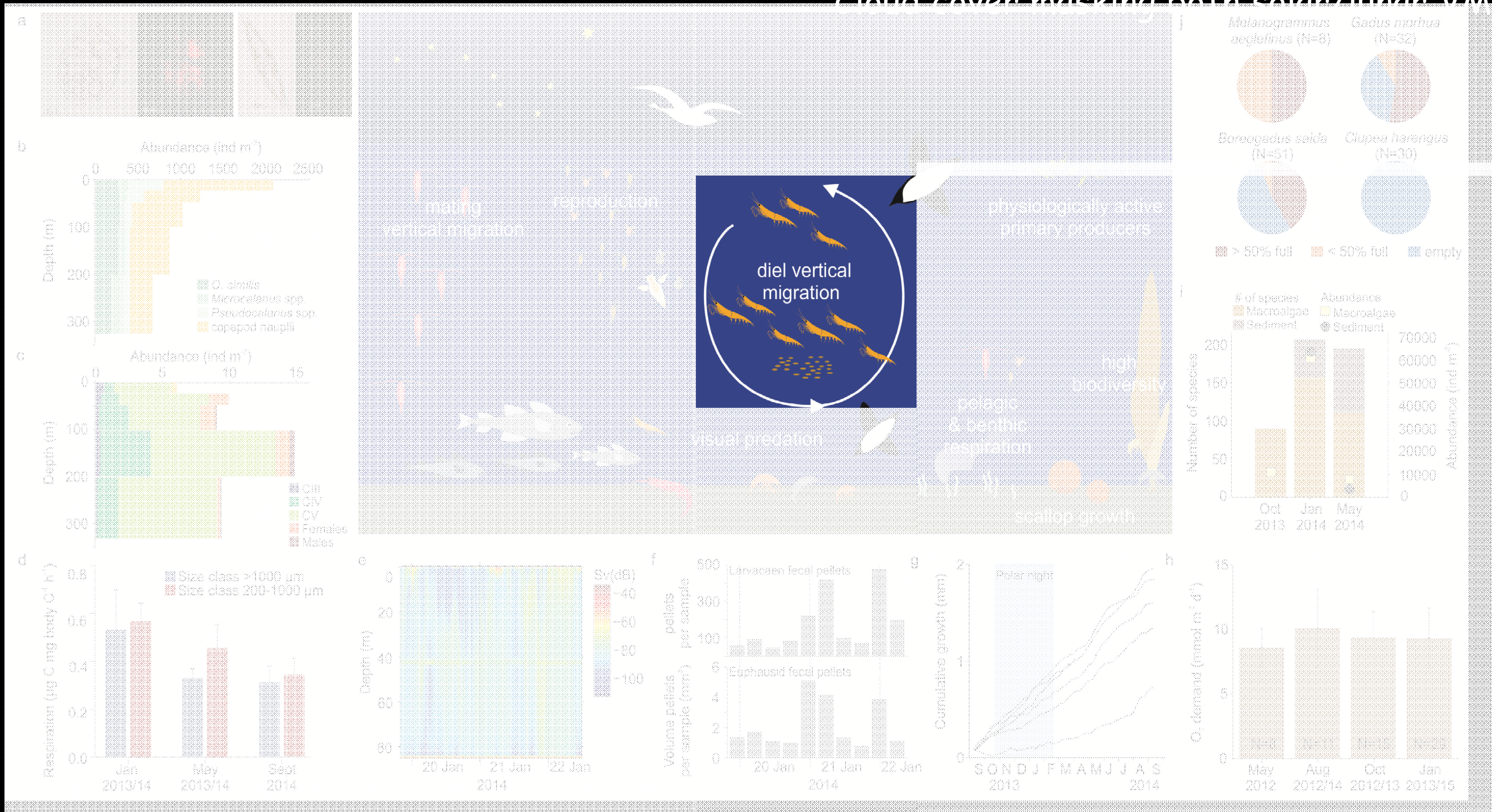
Rather a lot going on…

Lunar-day 24.8 $h^{-1}$ VM

Lunar-month 28 $d^{-1}$ VM

Lunar-month masking of solar DVM

Cloud cover masking both solar/lunar VM



To summarize

- Twenty years of data from across all marine domains of the Arctic (fjord, coast, shelf, ocean) show a uniform behaviour of zooplankton, where vertical migration during the polar night is driven by lunar illumination.

- The level of activity during the times of the full moon is unexpected and is independent of ice-cover.

To speculate *(in the words of Andrew Brierley):*

- *Since the vertical migration is vital for the biological carbon pump that has to date sequestered the equivalent of 200 ppm atmospheric CO2 in to the ocean (Giering et al. 2014).*

- *It had been speculated that loss of sea ice might impact DVM, but our data suggest this is not the case: the DVM-mediated element of the carbon cycle in the high Arctic might be resilient to change since DVM occurs irrespective of ice-cover.*

- *This has major implications for Arctic food-webs blah blah….*