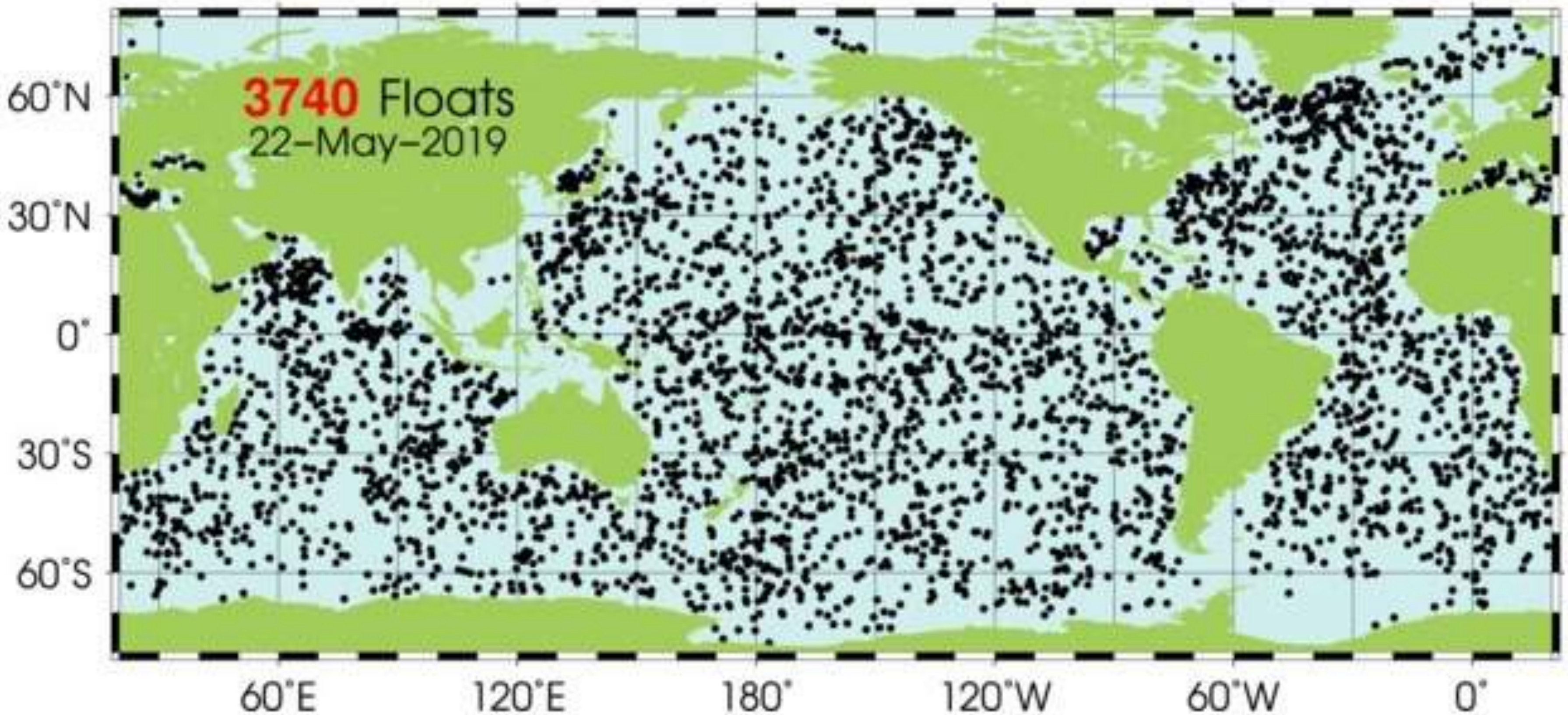
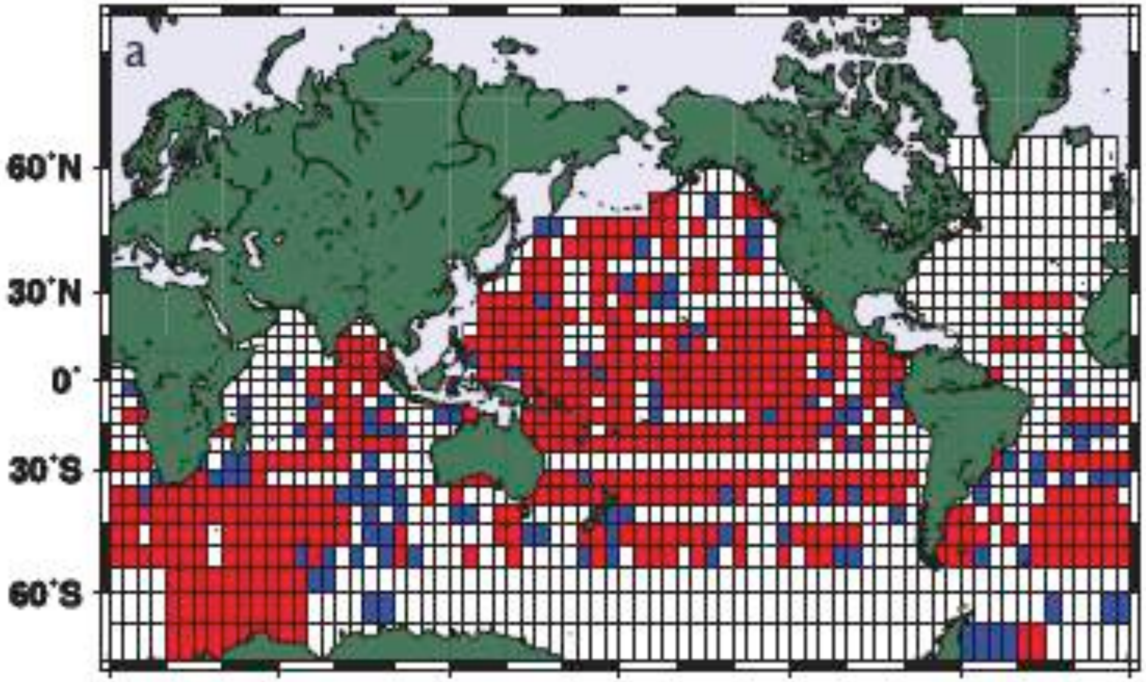
Observing the Ocean with Argo: Past, Present, Future



Stephen C. Riser
University of Washington
Seattle, WA USA

http://flux.ocean.washington.edu/riser_web

ECCO Summer School
Friday Harbor, WA
May 23, 2019

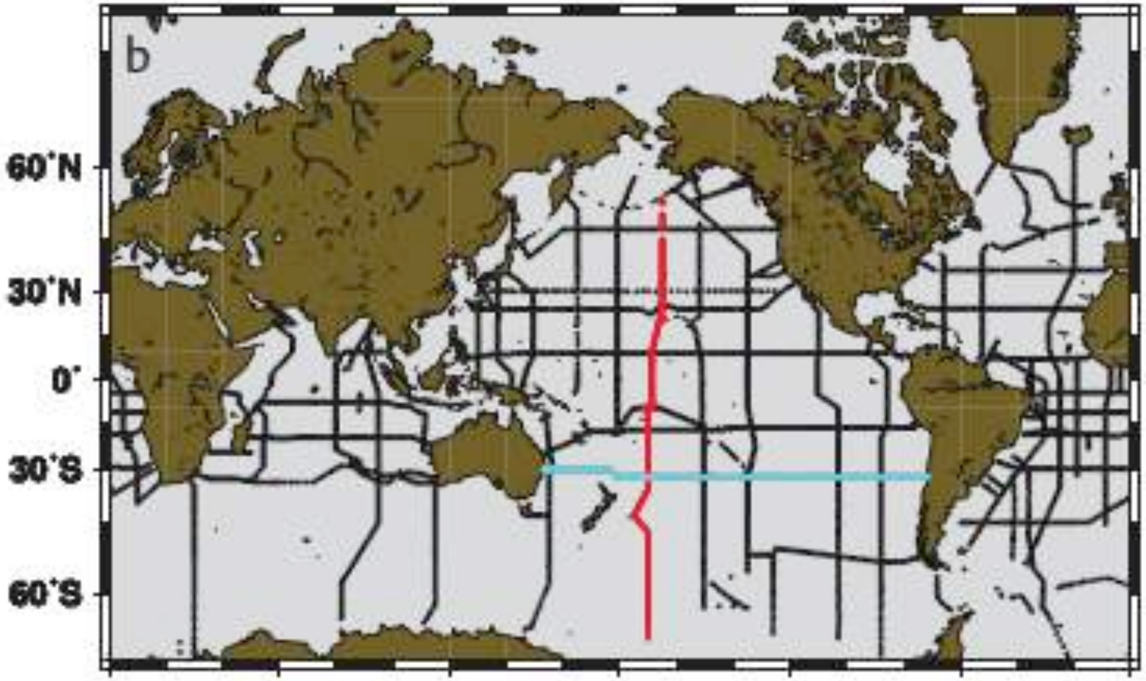


White: **at least one good *T/S* station to the bottom in a 5° square**

Red: **no *T/S* measurements to the bottom in a 5° square**

Blue: **bottom shallower than 2000 m**

[Worthington, 1981]



Hydrographic lines carried out as part of the World Ocean Circulation Experiment (WOCE), 1985-1998

The Original Argo Implementation Plan (1998)

On The Design and Implementation of Argo

A Global Array of Profiling Floats

The Argo Science Team[1]

[1] Dean Roemmich (chair), Olaf Boebel, Howard Freeland, Brian King, Pierre-Yves LeTraon, Robert Molinari, W. Brechner Owens, Stephen Riser, Uwe Send, Kensuke Takeuchi, Susan Wijffels.

Preface

This document describes some initial ideas for the design and implementation of *Argo*, a global array of autonomous profiling floats. The original concept grew out of two independent, but connected, initiatives, "*A Proposal for Global Ocean Observations for Climate: the Array for Real-time Geostrophic Oceanography*" (ARGO), by Dean Roemmich, and "*A program for Global Ocean SAlinity MonitORing*" (GOSAMOR), by Ray Schmitt. Early in 1998 the International Steering Team for GODAE (the Global Ocean Data Assimilation Experiment) endorsed the broad concept of such an array and undertook to develop a plan. In the 2nd quarter of 1998 the Upper Ocean Panel of CLIVAR also considered these proposals and unanimously agreed that such an initiative must be given high priority in the CLIVAR Implementation plans.

In July of 1998 a Workshop was held in Tokyo to discuss the prospects for *Argo* and an initial outline for a plan was drawn up. At that Workshop, which was jointly convened by GODAE and the CLIVAR UOP, an *Argo* Science Team was appointed with the charge to produce an initial design and implementation plan. The present document is the response to that charge.

An initial draft of this document was widely circulated through the oceanographic and climate community for review. This review drew many comments and suggestions and raised a number of significant issues. Because of time constraints, and the need to have a document available for the CLIVAR Conference in December of 1998, we, as Chairs of the convening bodies, decided that a detailed revision was not wise, and probably not possible, on this time frame. Many of the issues require detailed scientific study and need some time for fuller consideration. As an interim measure, we have attended to a few of the more pressing issues, and prepared a consolidated list of issues and items for consideration by the Science Team at a later time.

This document then represents an initial set of ideas for the design and implementation of *Argo*, and presents the scientific rationale for proceeding with *Argo*. We think you will find the case for *Argo* a strong one, and that the initiative, though ambitious, both doable and worth doing.

We thank the *Argo* Science Team, and other contributors, for this paper, and look forward to the early development of a more detailed design and complete implementation plan.

Neville Smith
Chair of the International GODAE Steering Team

and

Chet Koblinsky
Chair of the CLIVAR Upper Ocean Panel

Argo was conceived as a program to:

- Sample the oceanic heat and freshwater content globally using profiling floats
- Examine the climate scale of variability (> 10^3 km, > seasonal cycle)
- Pr
- Sa
- Sa
- M
- W

Results since 1999:

- 3000 float array first achieved in 2007
- 32 nations now participating (US provides 50% of the floats)
- Presently over 2 million quality profiles
- Data is available in near real-time
- Floats sampling to 2000 m, many lasting 6 years
- > 3700 papers in refereed journals

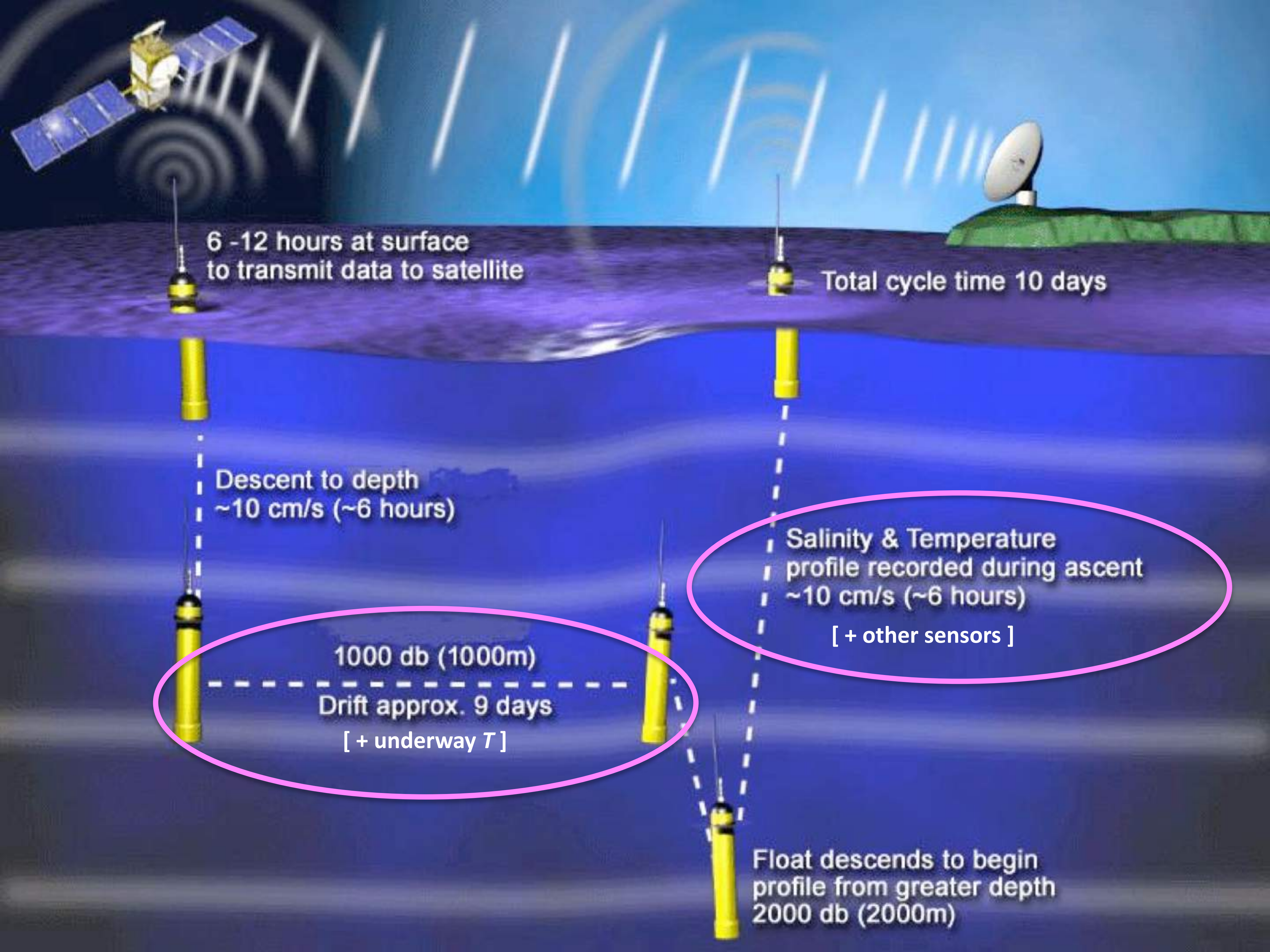
[see *http://www.argo.ucsd.edu/links.html* for a list of sites where data and data products are available]

A p ... uire:

- A
- Mean float lifetime > 5 years (100 profiles) ??
- *T*, *S*, and *p* observations of sufficient accuracy and precision ??
- A data system capable of both real-time and delayed-mode editing ??

Floats at UW

An array of profiling floats


6 -12 hours at surface
to transmit data to satellite
Total cycle time 10 days
Descent to depth
~10 cm/s (~6 hours)
Salinity & Temperature
profile recorded during ascent
~10 cm/s (~6 hours)
[+ other sensors]
1000 db (1000m)
Drift approx. 9 days
[+ underway *T*]
Float descends to begin
profile from greater depth
2000 db (2000m)

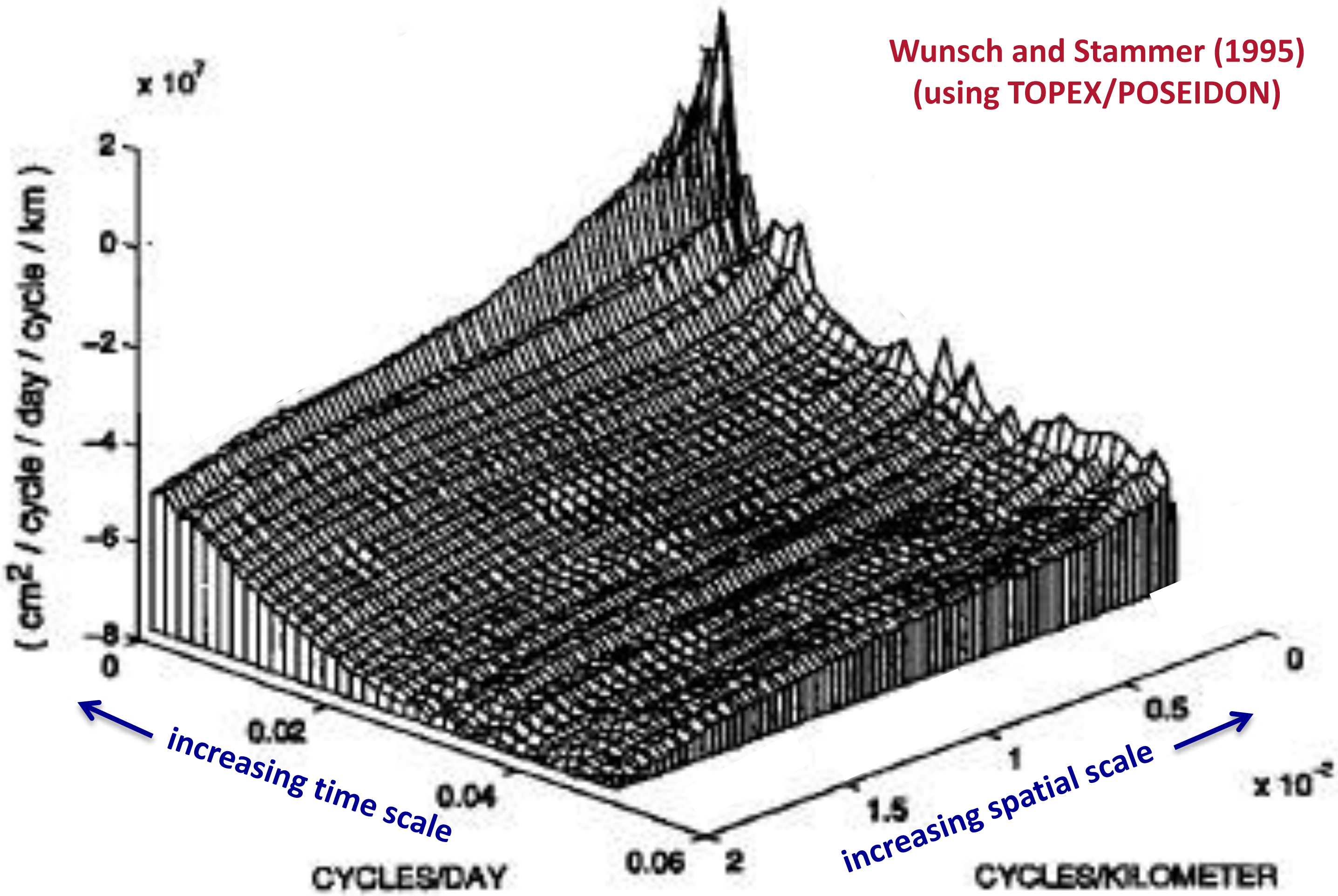
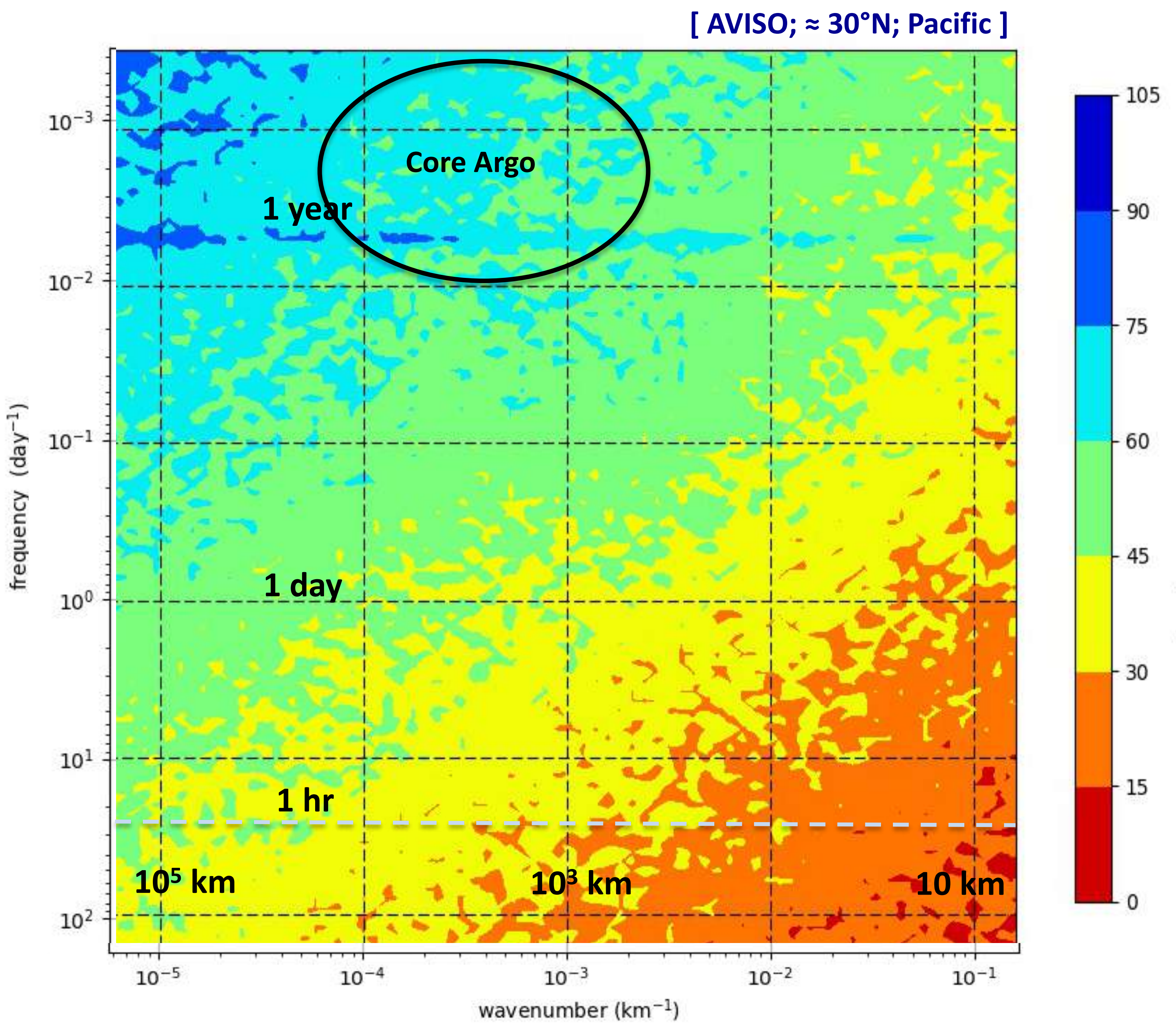
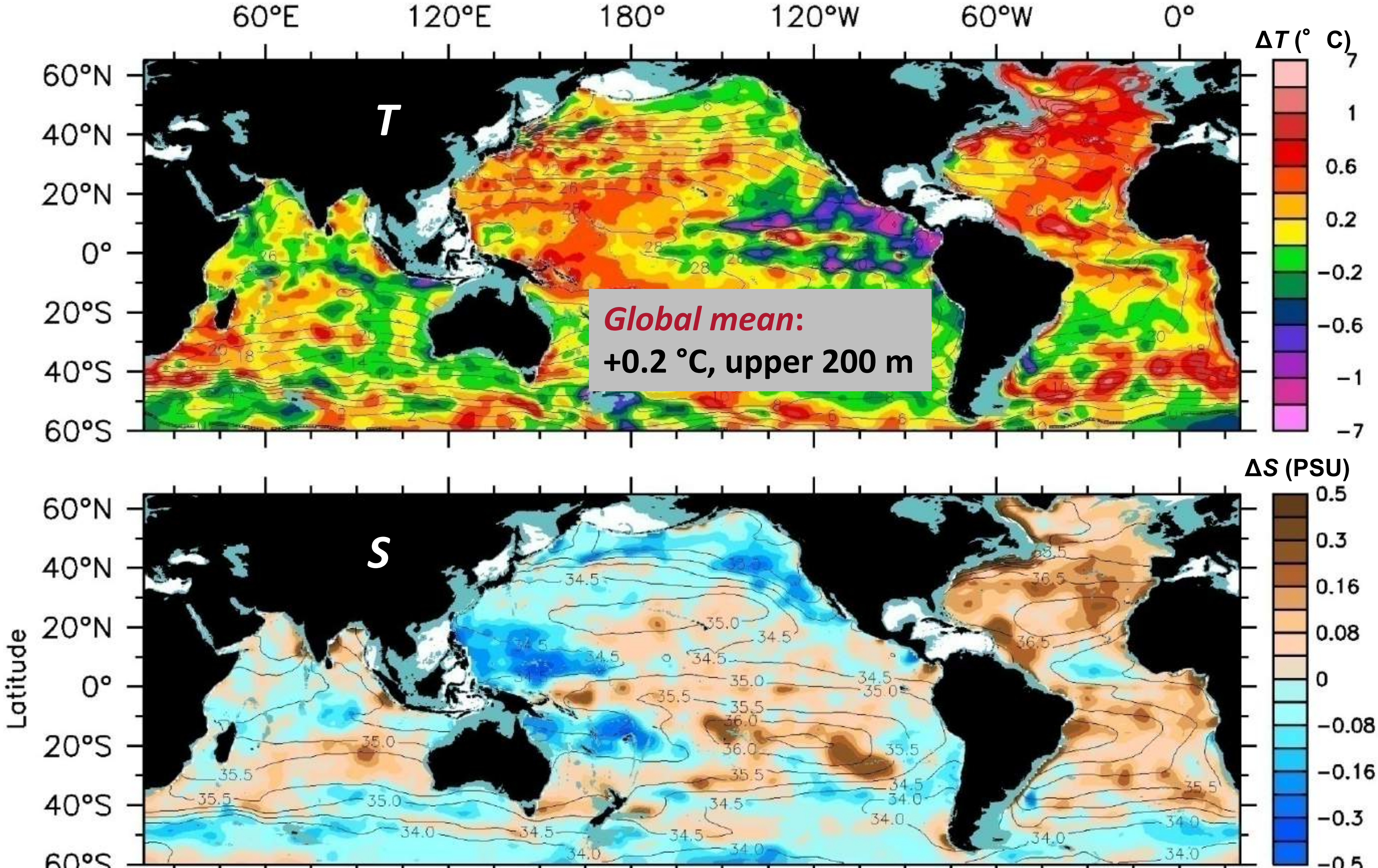


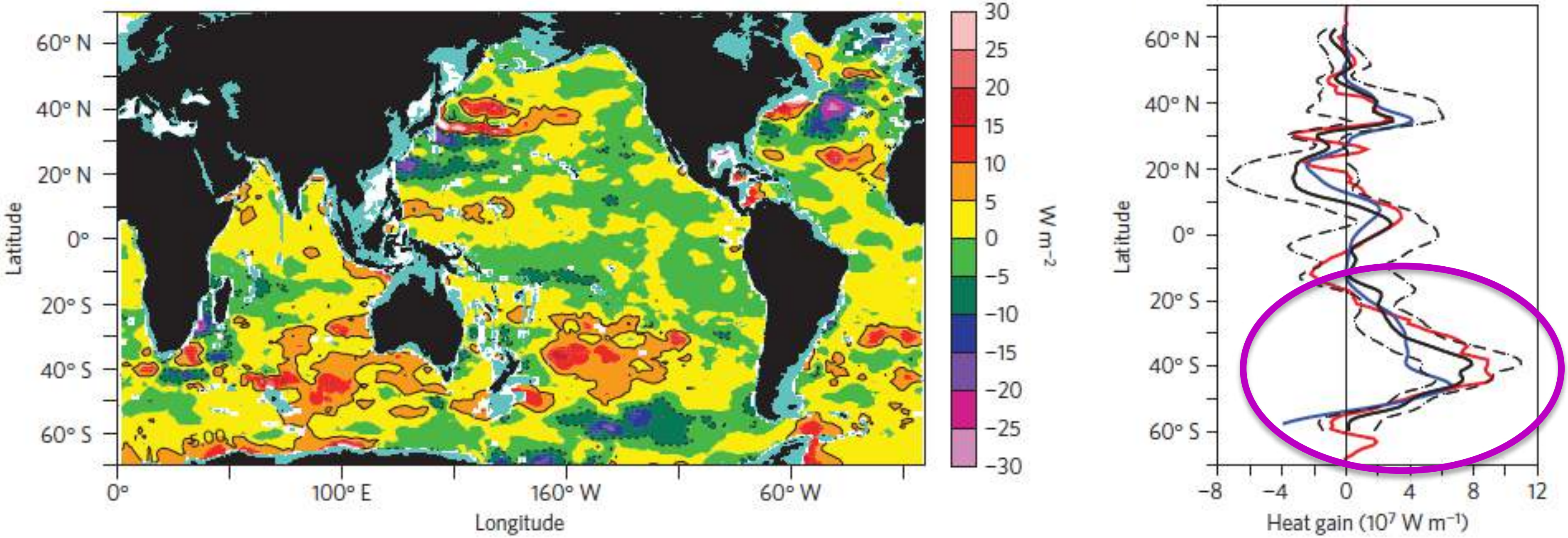
Figure 7a. Frequency-wavenumber power density spectrum of the global ocean as inferred from the spherical harmonic fit converted to along-track coordinates. (No averaging was done.) The annual peak is the most conspicuous feature.


[AVISO; ≈ 30°N; Pacific]
Core Argo
1 year
1 day
1 hr
10⁵ km
10³ km
10 km
frequency (day⁻¹)
10⁻³
10⁻²
10⁻¹
10⁰
10¹
10²
wavenumber (km⁻¹)
10⁻⁵
10⁻⁴
10⁻³
10⁻²
10⁻¹
Sea Level Variance (cm²)
105
90
75
60
45
30
15
0

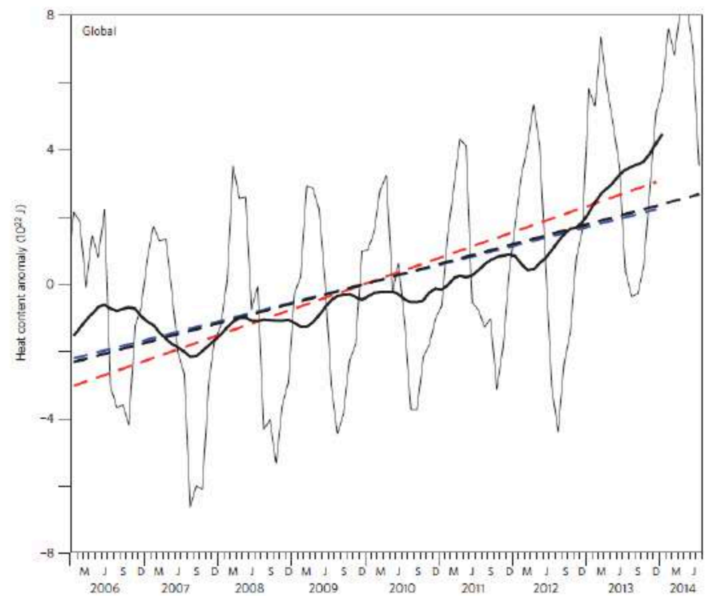


Changes in upper 150 m temperature and salinity between 2004-2008 and mid-1980s (Roemmich and Gilson, 2009)

[see also an analysis of a 50-year trend in salinity by Durack and Wijffels, 2010]

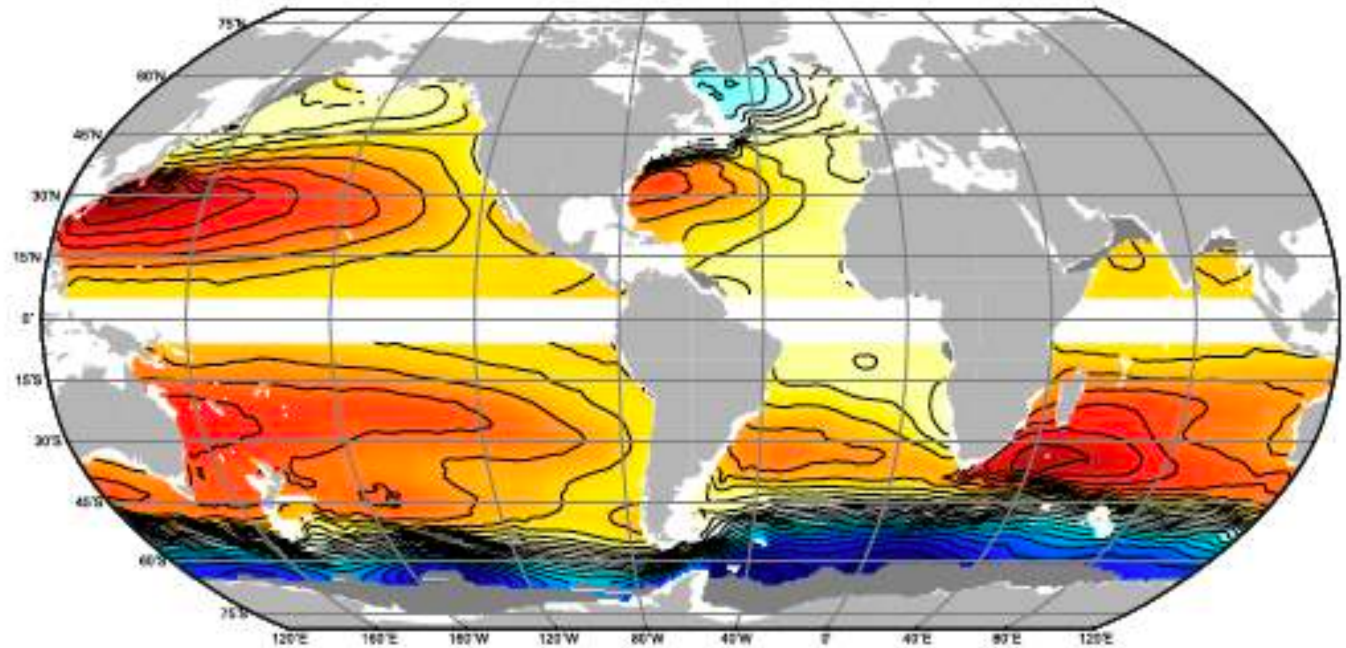


Change in upper ocean heat content, from Roemmich et al. (2015)



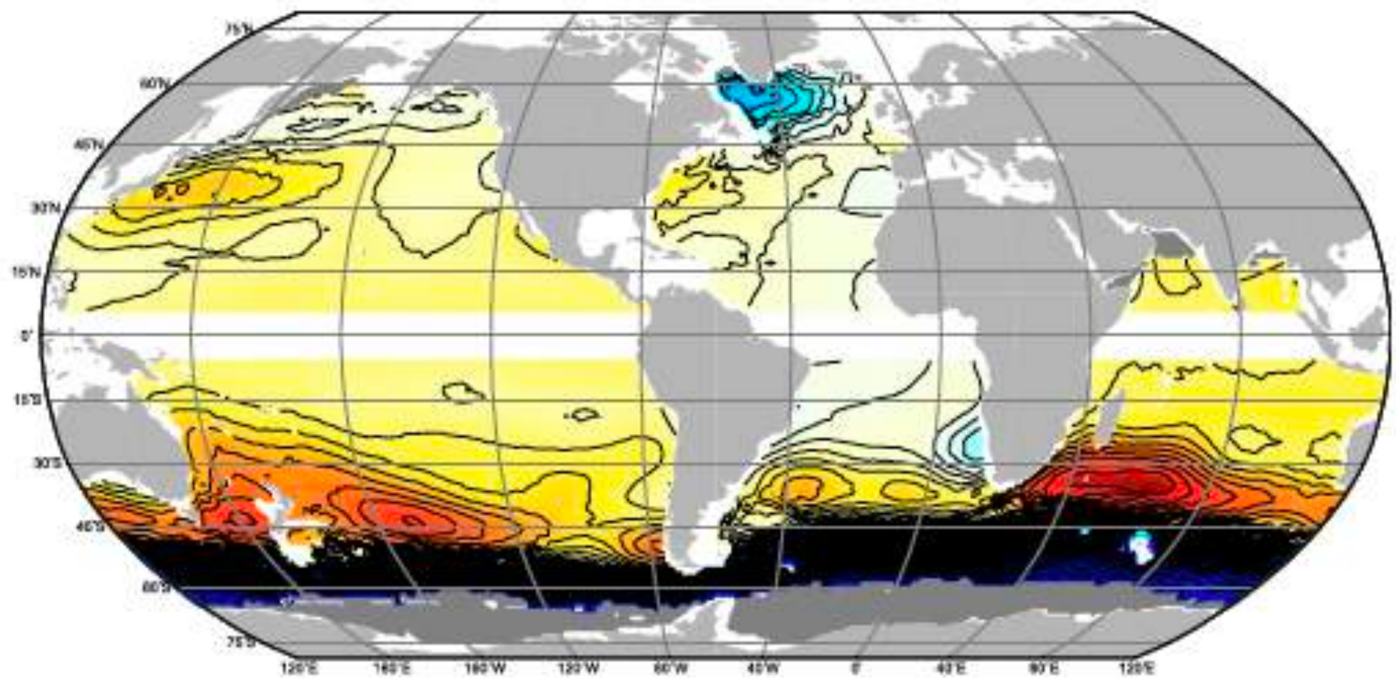
Result: global heating at a rate of 0.4-0.6 W/m^2, 2006-2013

200 m, CI = 10 dyn cm

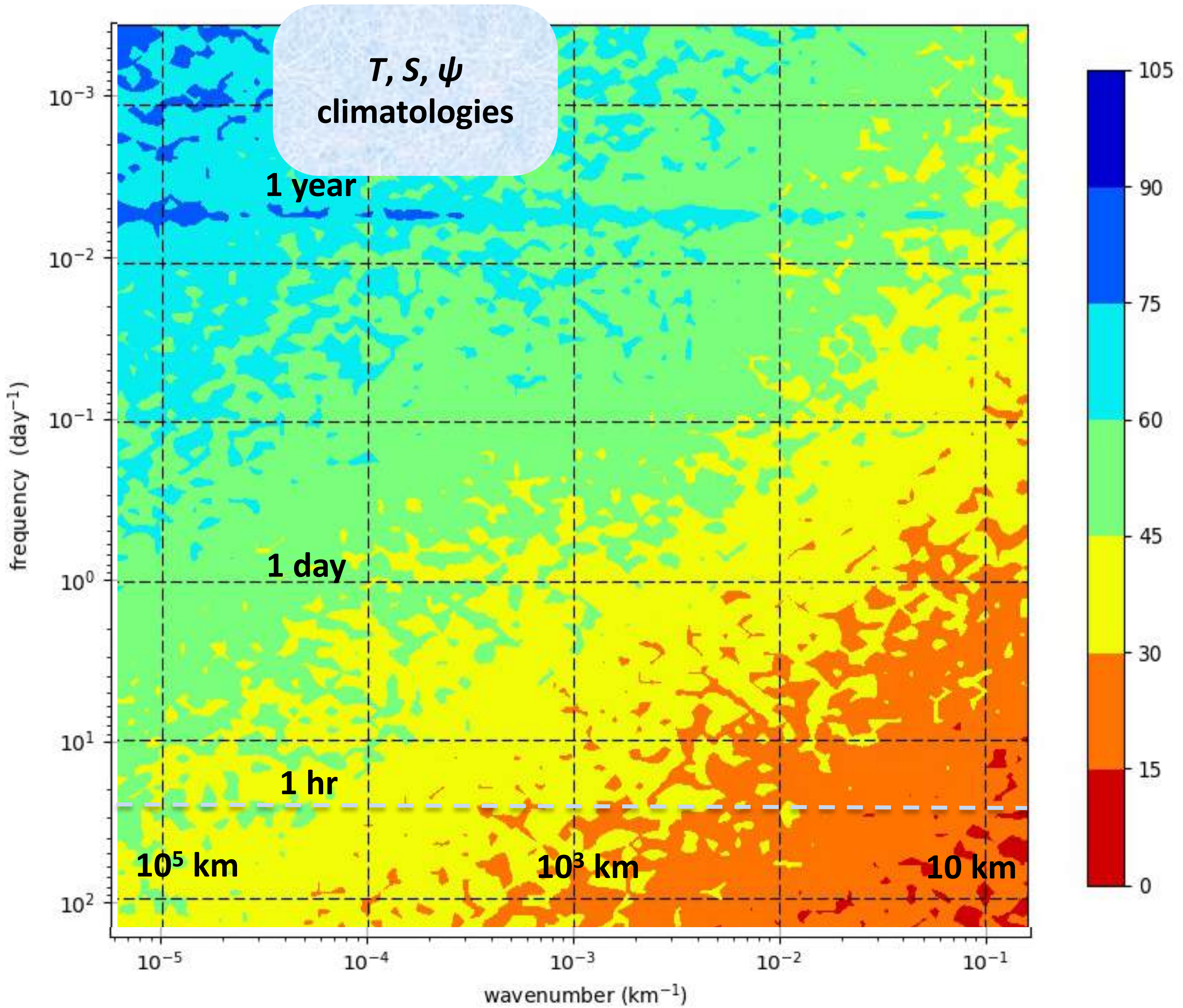


Absolute geostrophic streamfunction from Argo data, 2004-2010 (Gray and Riser, 2014)

1000 m, CI = 5 dyn cm

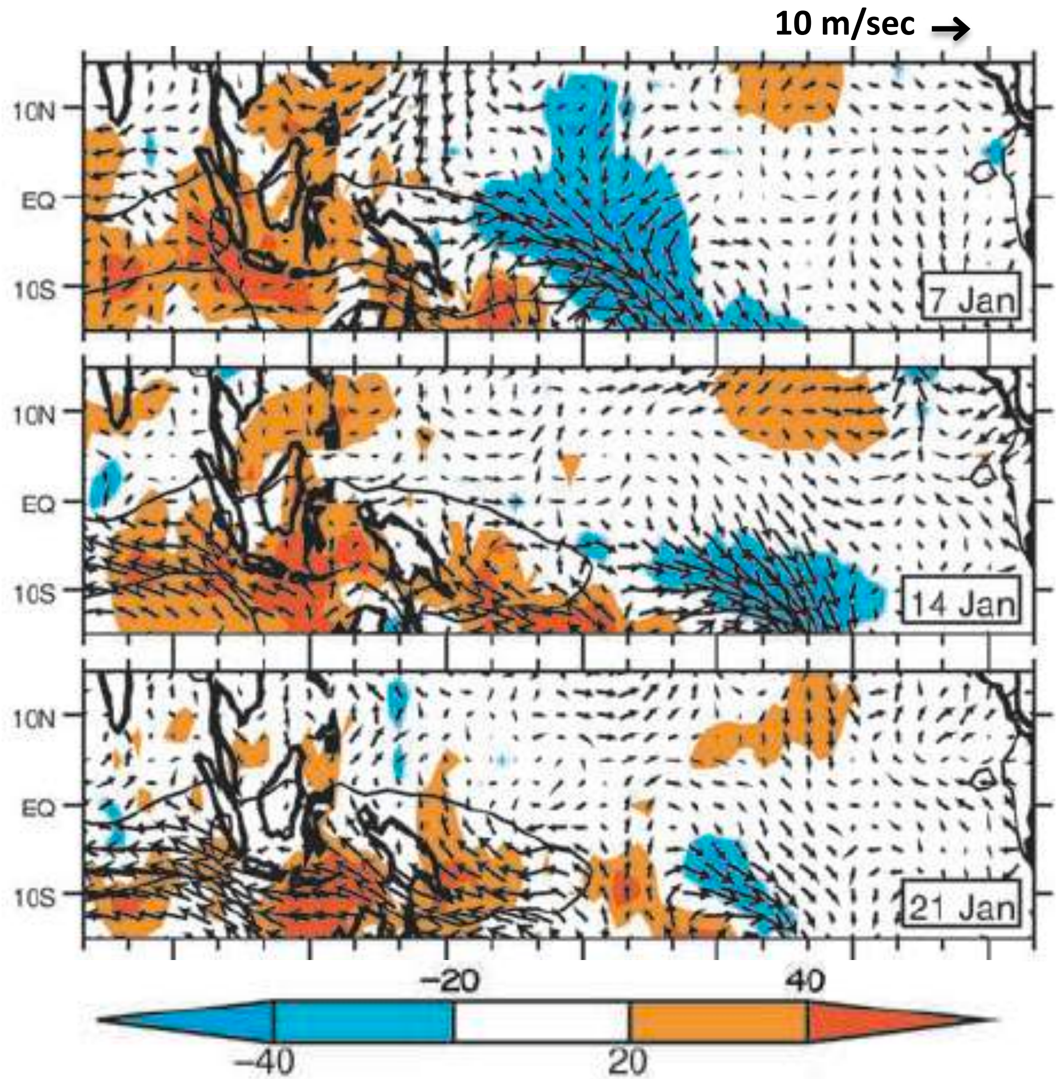


[see also the ANDRO and YoMaHa climatologies]

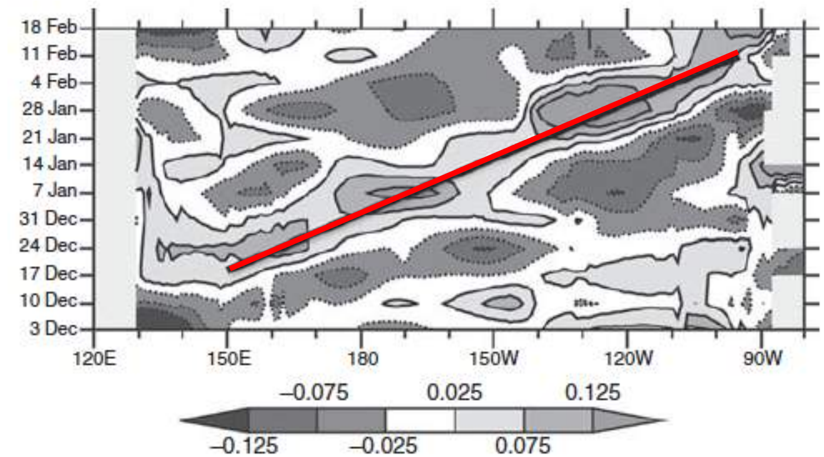


T, S, ψ
climatologies
1 year
1 day
1 hr
10⁵ km
10³ km
10 km
frequency (day⁻¹)
wavenumber (km⁻¹)
Sea Level Variance (cm²)
105
90
75
60
45
30
15
0
10⁻³
10⁻²
10⁻¹
10⁰
10¹
10²
10⁻⁵
10⁻⁴
10⁻³
10⁻²
10⁻¹

Argo floats and MJO

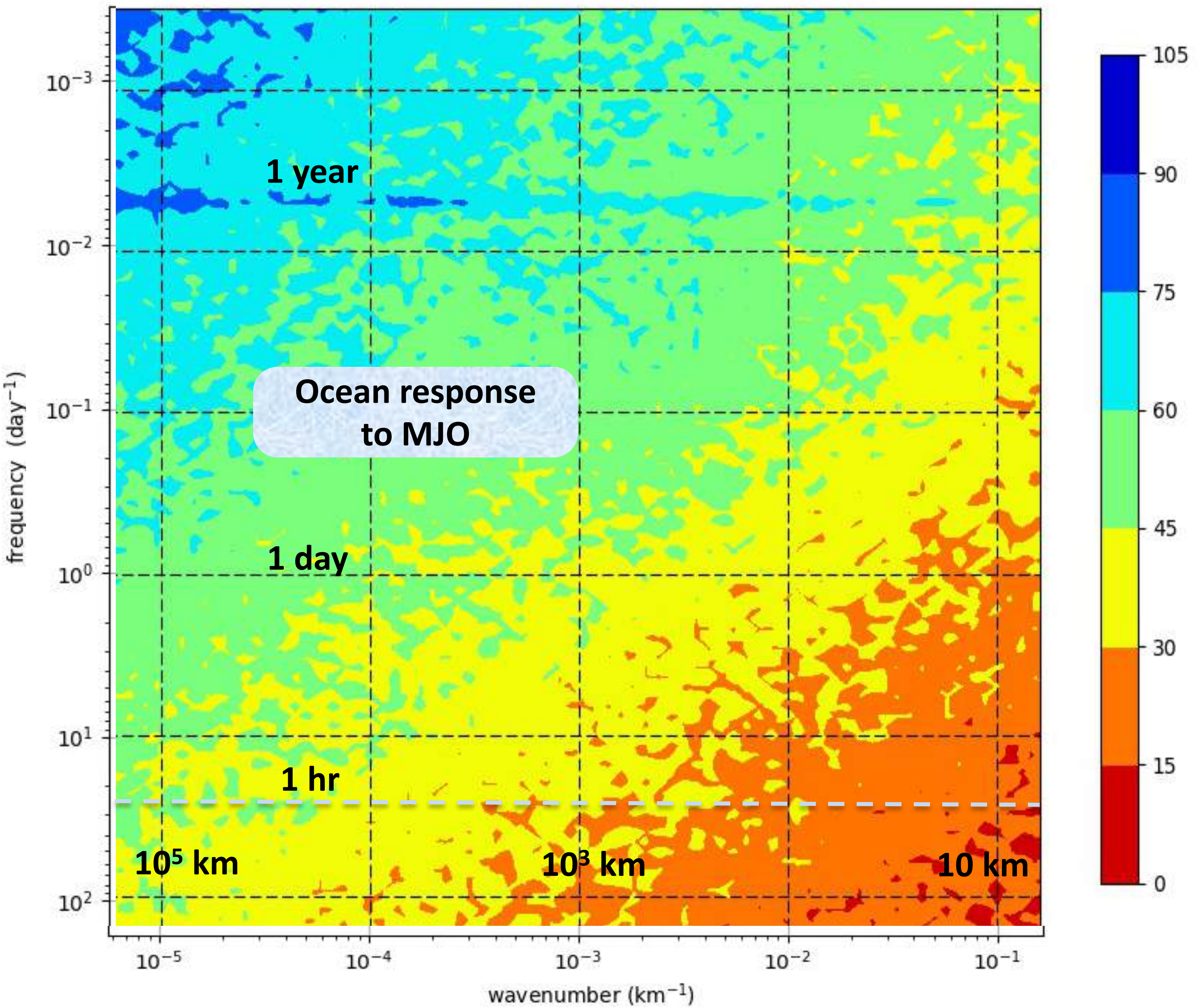


OLR anomaly (W/m^2); 1000 hPa wind anomalies



Longitude-time section of 850 m Argo temperature averaged 5°S to 5°N, plus the phase propagation of the down-welling Kelvin wave generated by the wind anomaly; a sub-thermocline response of the ocean to MJO

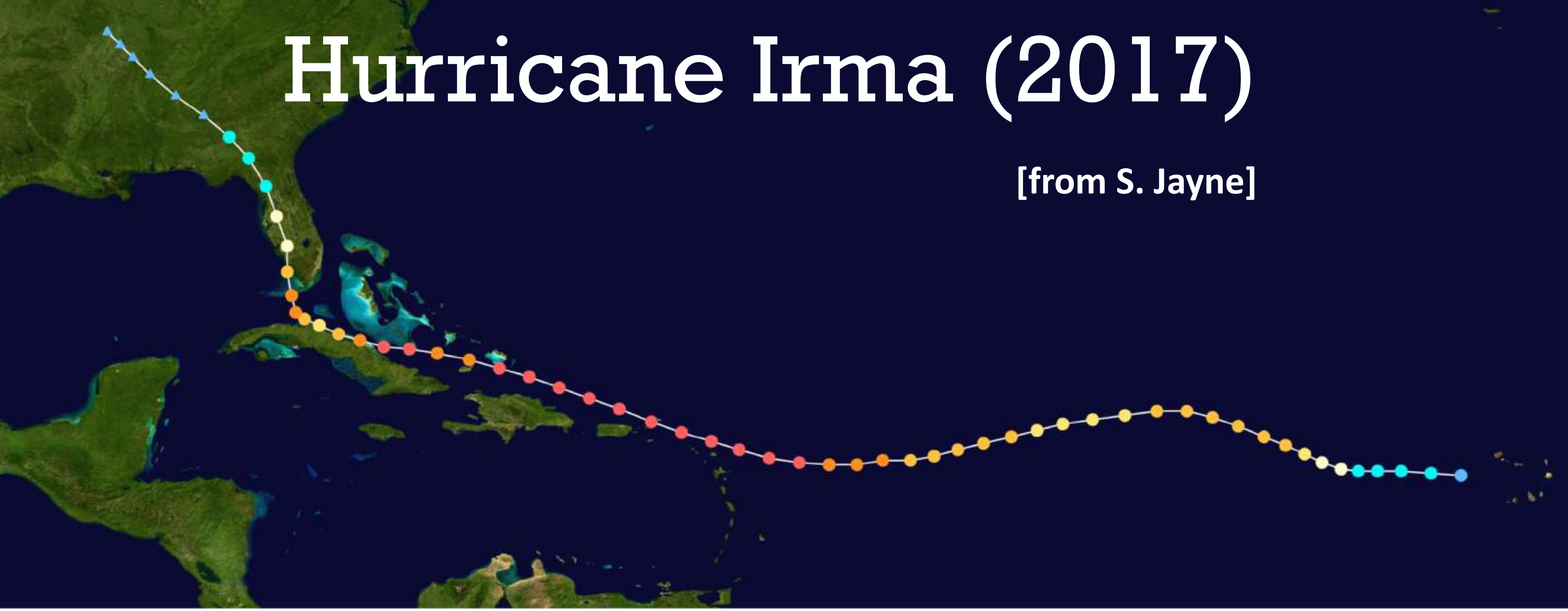
Matthews, Singhruck, and Heywood, *Science*, 2008

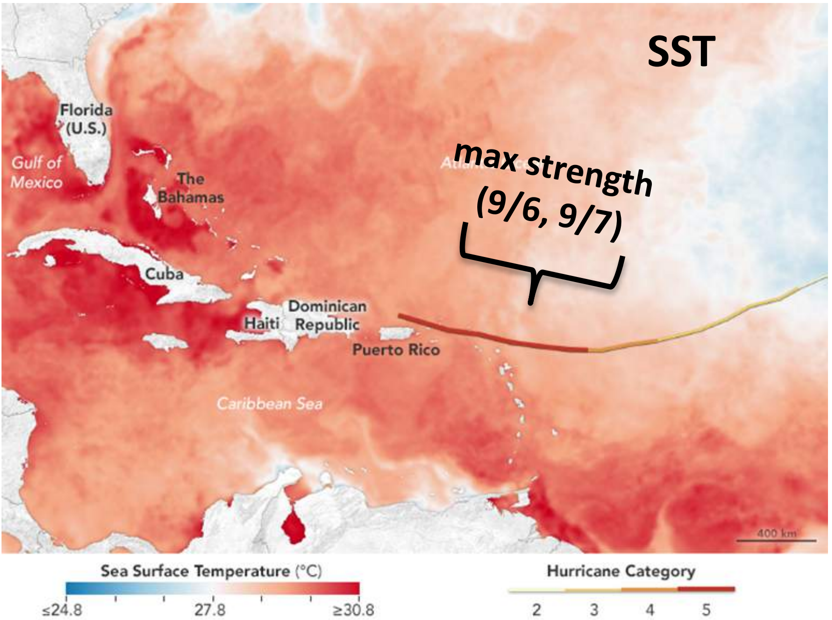


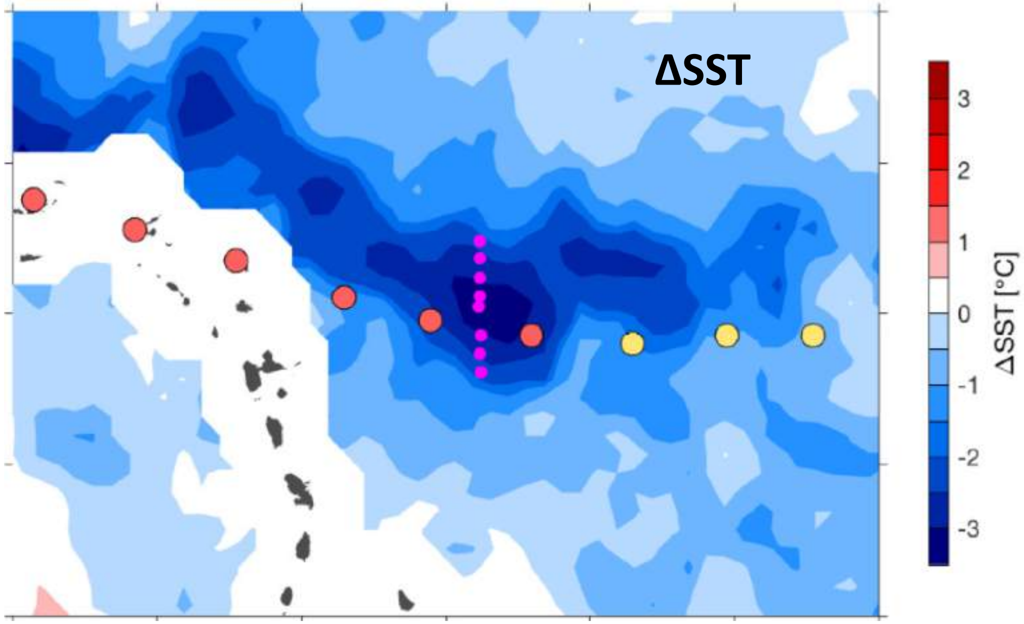
1 year
Ocean response to MJO
1 day
1 hr
10^5 km
10^3 km
10 km
frequency (day^-1)
wavenumber (km^-1)
Sea Level Variance (cm^2)
105
90
75
60
45
30
15
0

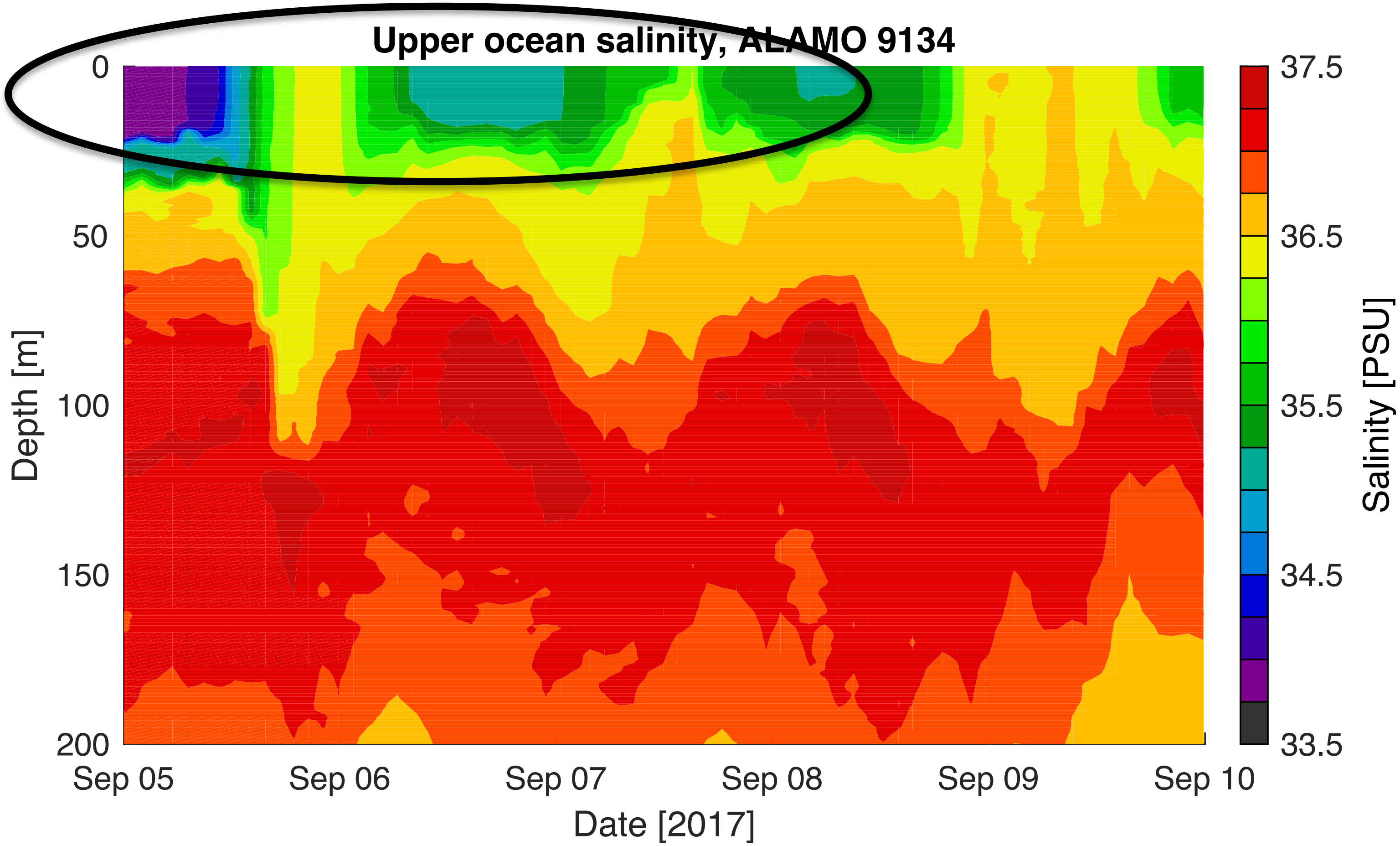
Hurricane Irma (2017)

[from S. Jayne]

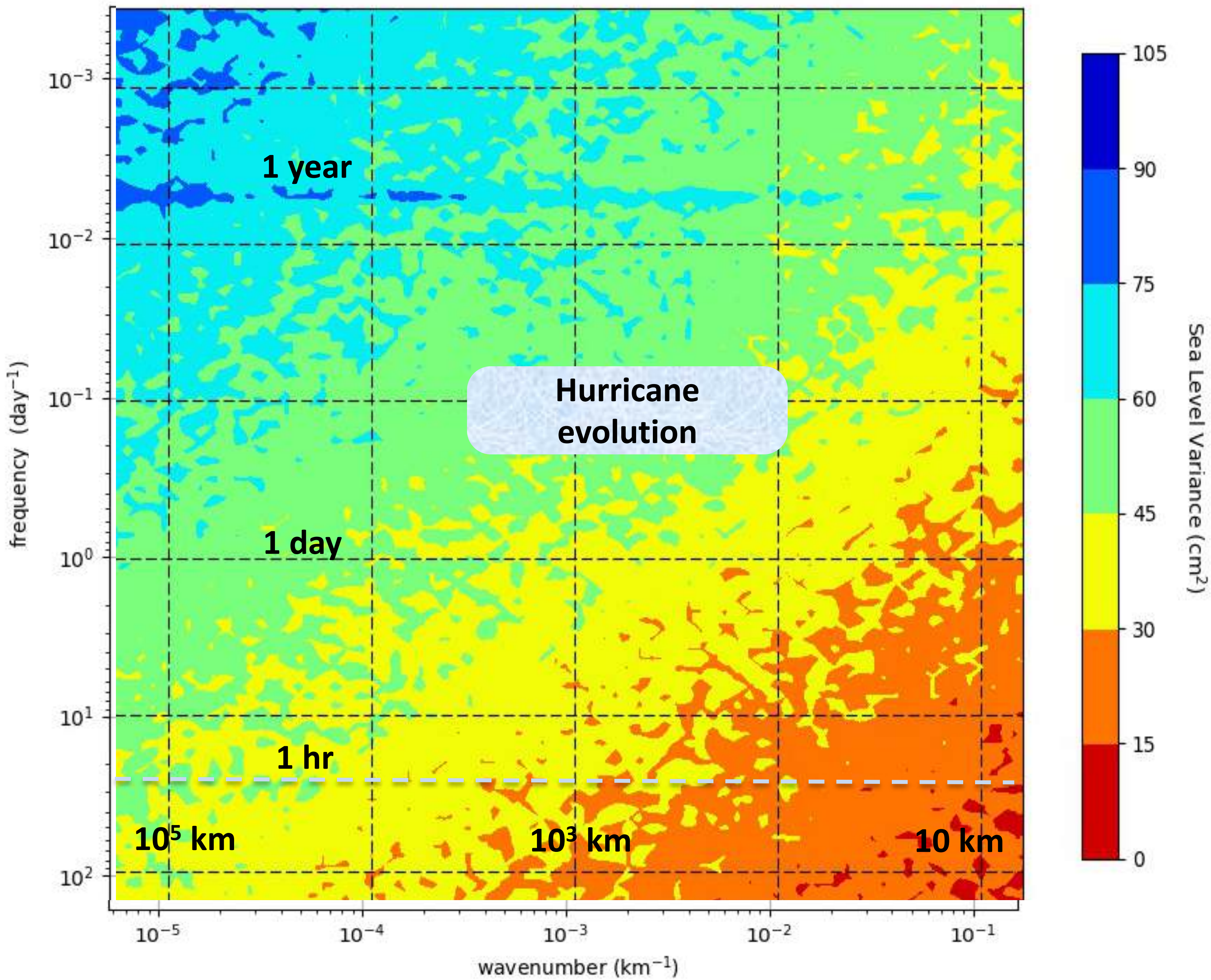




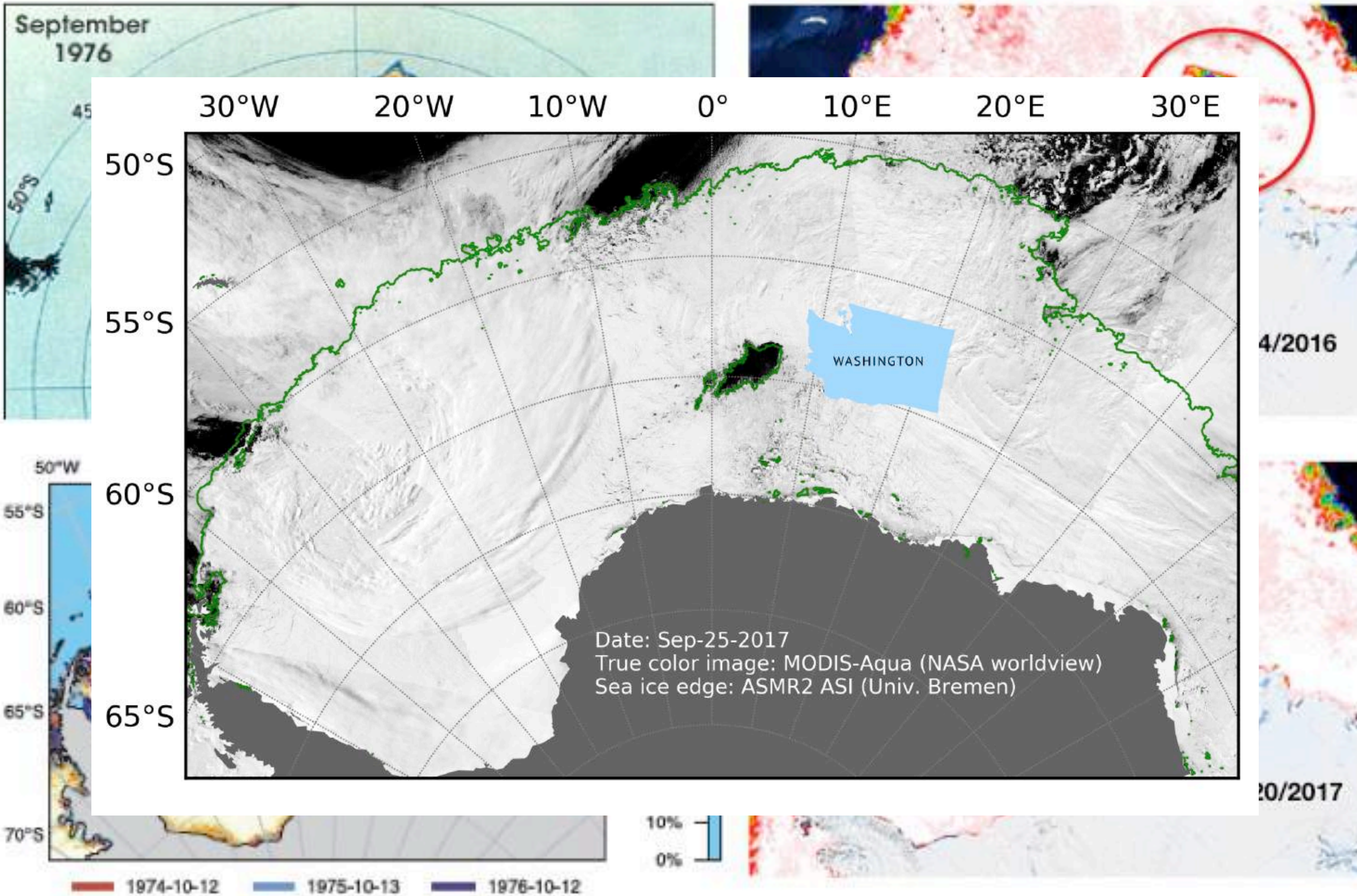




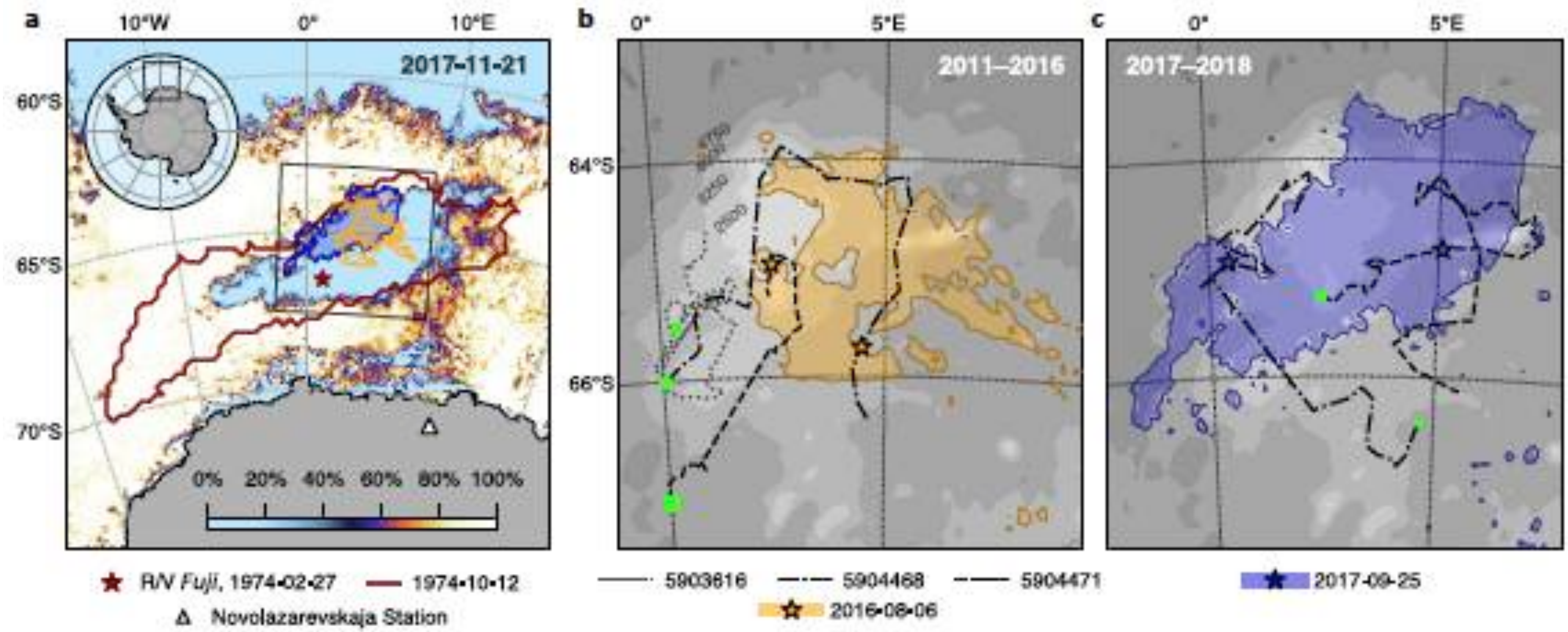
Results of rapid profiling by an Alamo float in the path of hurricane Irma in 2017. Such measurements allow the real-time evolution of the ocean to be viewed in near-real time and promise to be important in improving hurricane forecasts. [S. Jayne]



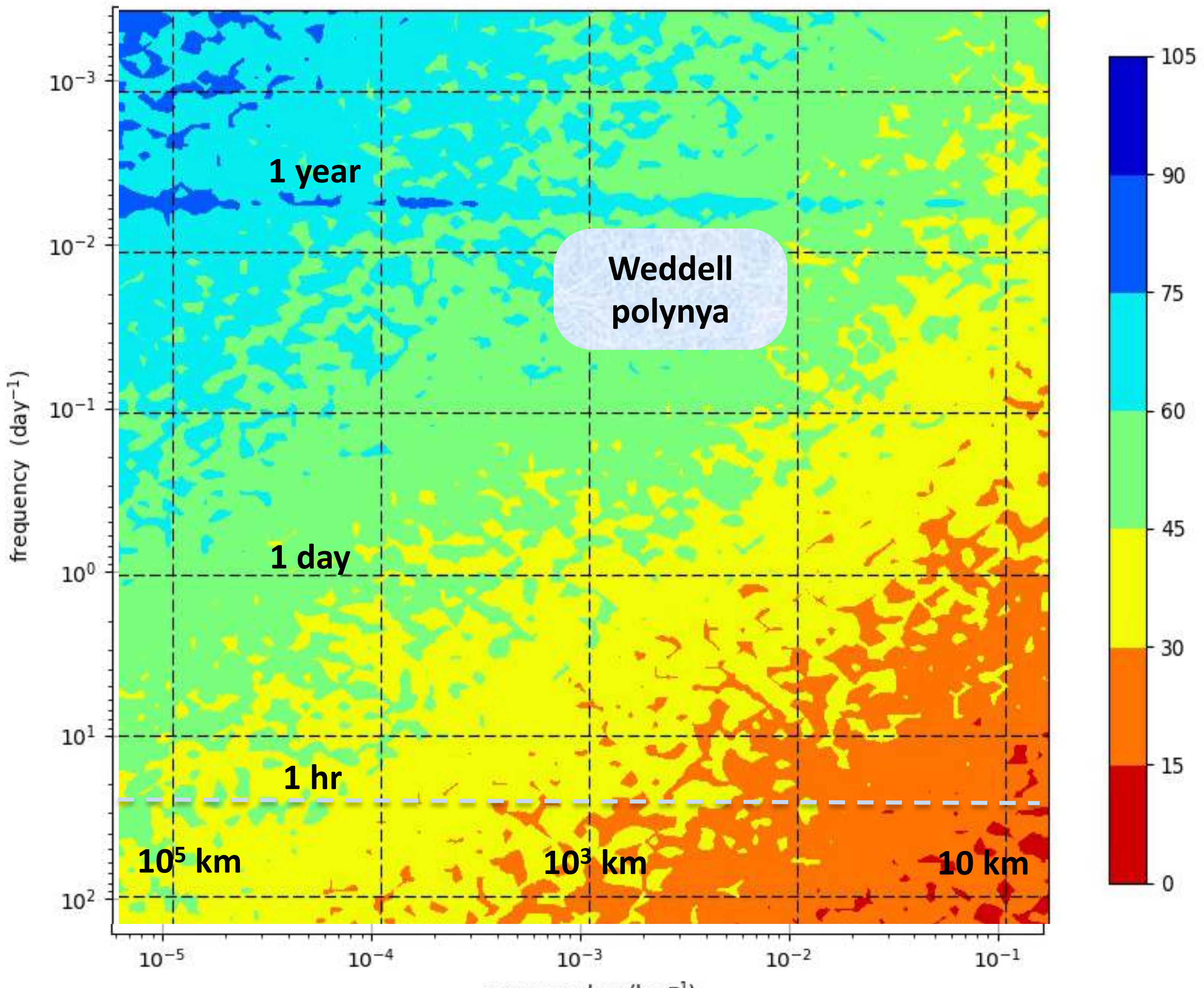
1 year
Hurricane evolution
1 day
1 hr
10^5 km
10^3 km
10 km
frequency (day^{-1})
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2
wavenumber (km^{-1})
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
Sea Level Variance (cm^2)
105
90
75
60
45
30
15
0



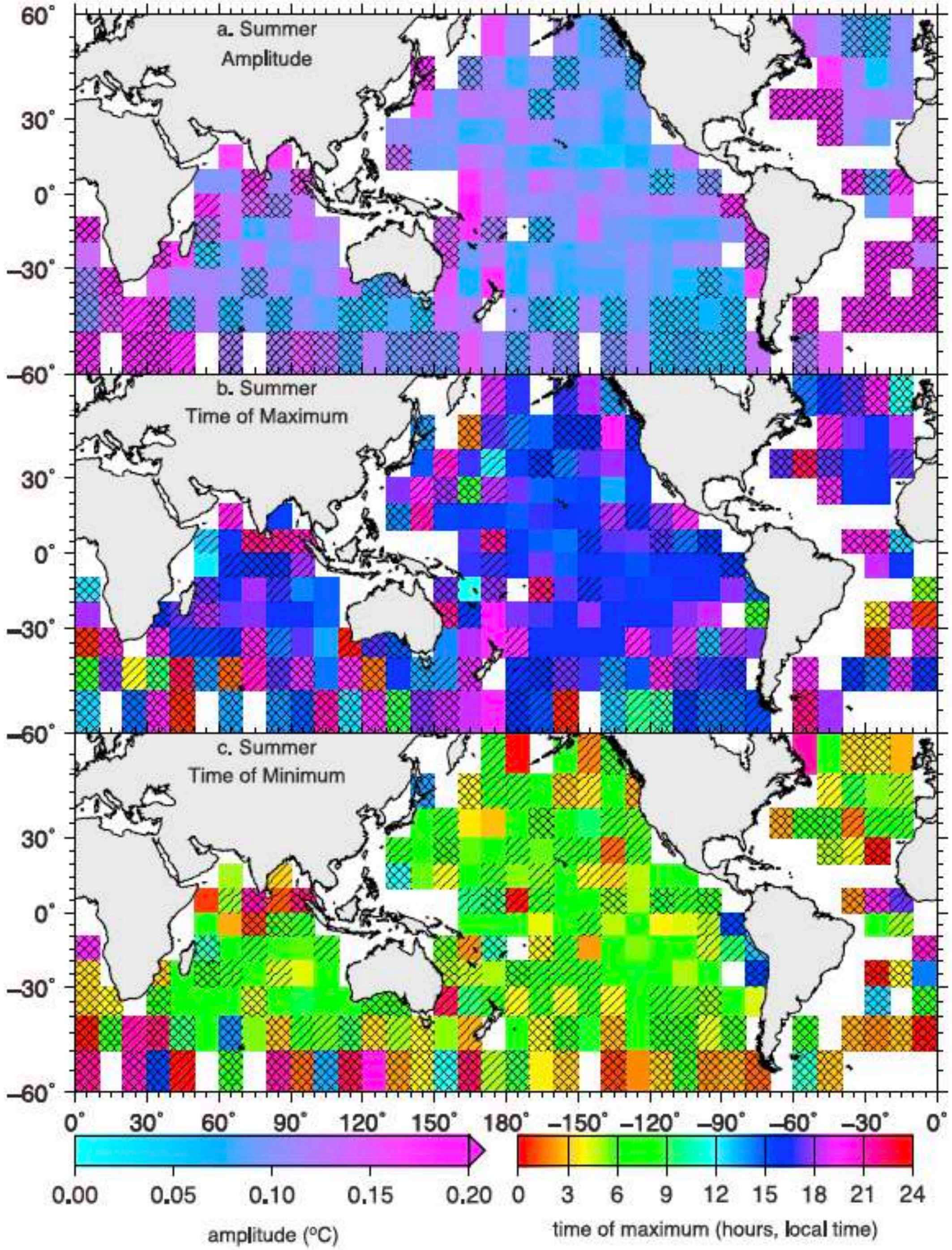
Polynyas in the Weddell Sea: 1970s, and 2016 and 2017



Argo floats in the 2016/2017 Weddell Sea polynyas
[Campbell et al., *Nature*, in press]

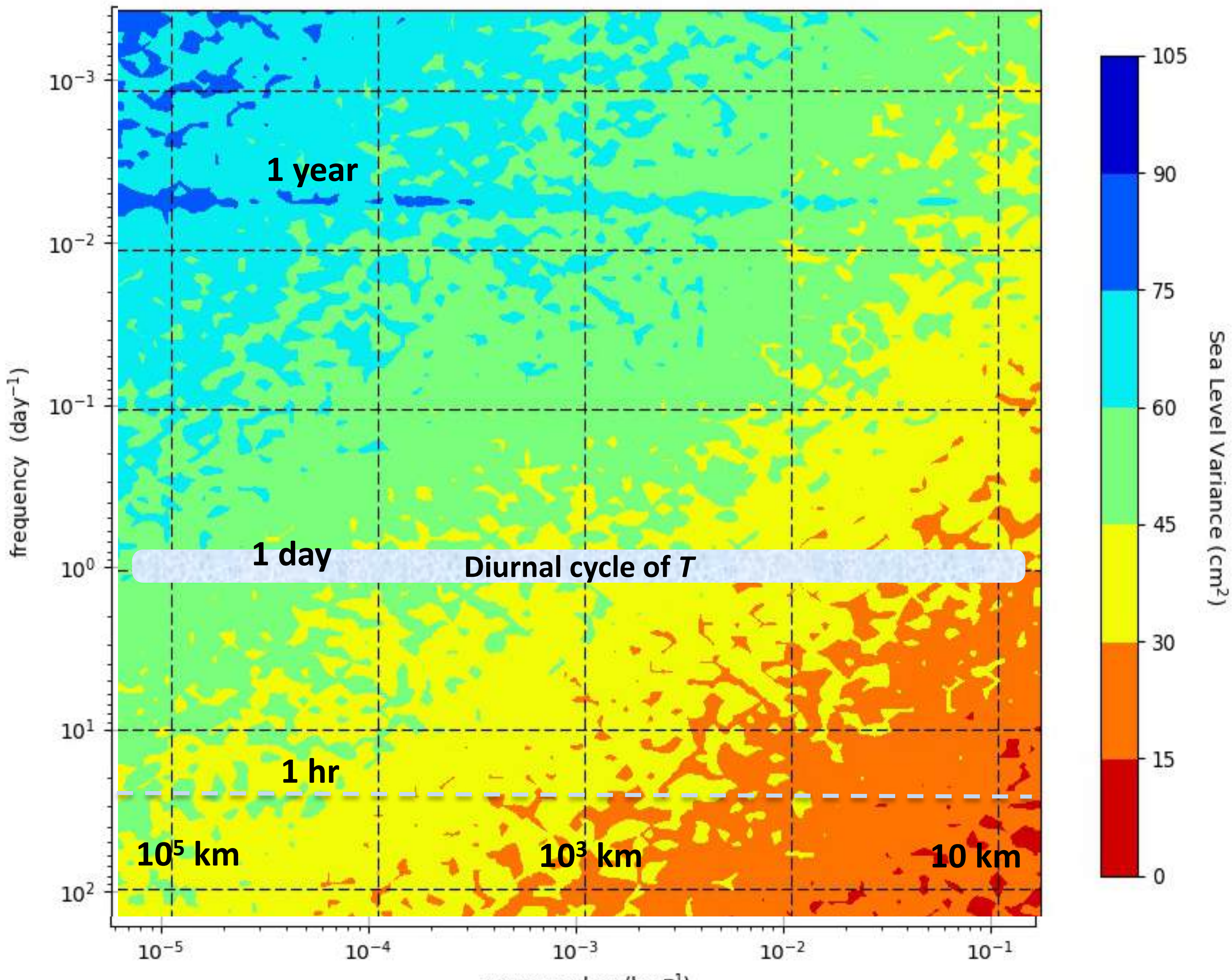


1 year
Weddell polynya
1 day
1 hr
10^5 km
10^3 km
10 km
frequency (day⁻¹)
wavenumber (km⁻¹)
Sea Level Variance (cm²)
105
90
75
60
45
30
15
0



The diurnal cycle of *T* in the world ocean (from Gille, 2012), using Argo profiles and satellite-derived SST data

(> 400K profiles used)



1 year
1 day
Diurnal cycle of T
1 hr
10^5 km
10^3 km
10 km
frequency (day^-1)
wavenumber (km^-1)
Sea Level Variance (cm^2)
105
90
75
60
45
30
15
0

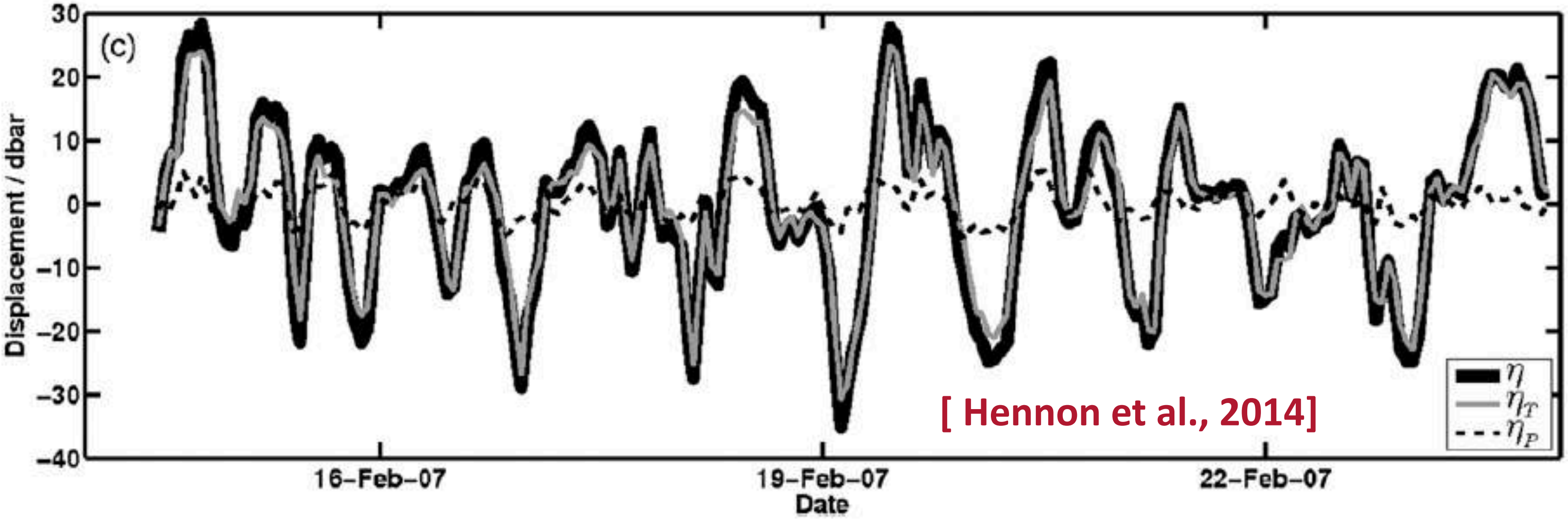
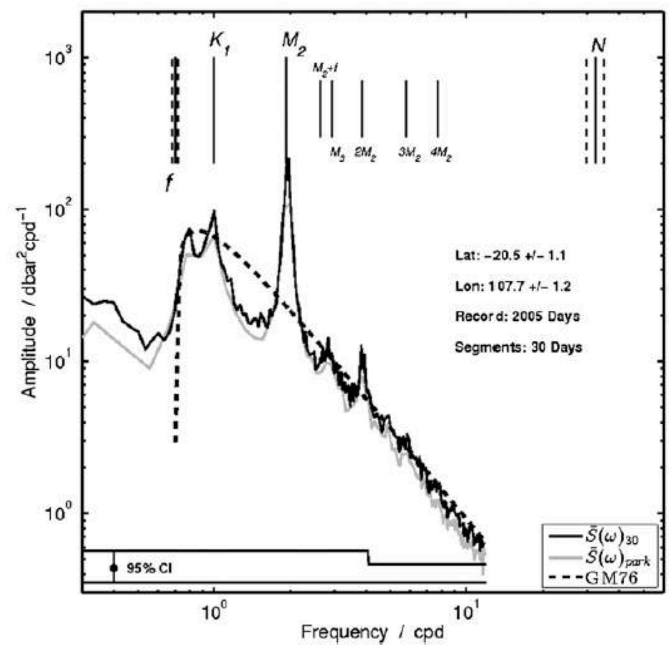


FIG. 3. (a) Raw park-phase temperature during cycle 22 for float 5135. (b) Raw park-phase pressure during cycle 22. (c) Processed isotherm displacement as seen by the float (gray), the float displacement (dashed), and the actual isotherm displacement (thick black) during the park phase of cycle 22

Many floats measure *T* and *p* at regular intervals (usually once per hour) during their park phase. Vertical displacement around floats during the park phase is often much larger than the actual vertical displacement, as inferred from the temperature and temperature gradient. From this, the vertical displacement spectrum at the park depth can be discerned, leading to an estimate of the spectrum of *internal gravity waves*.



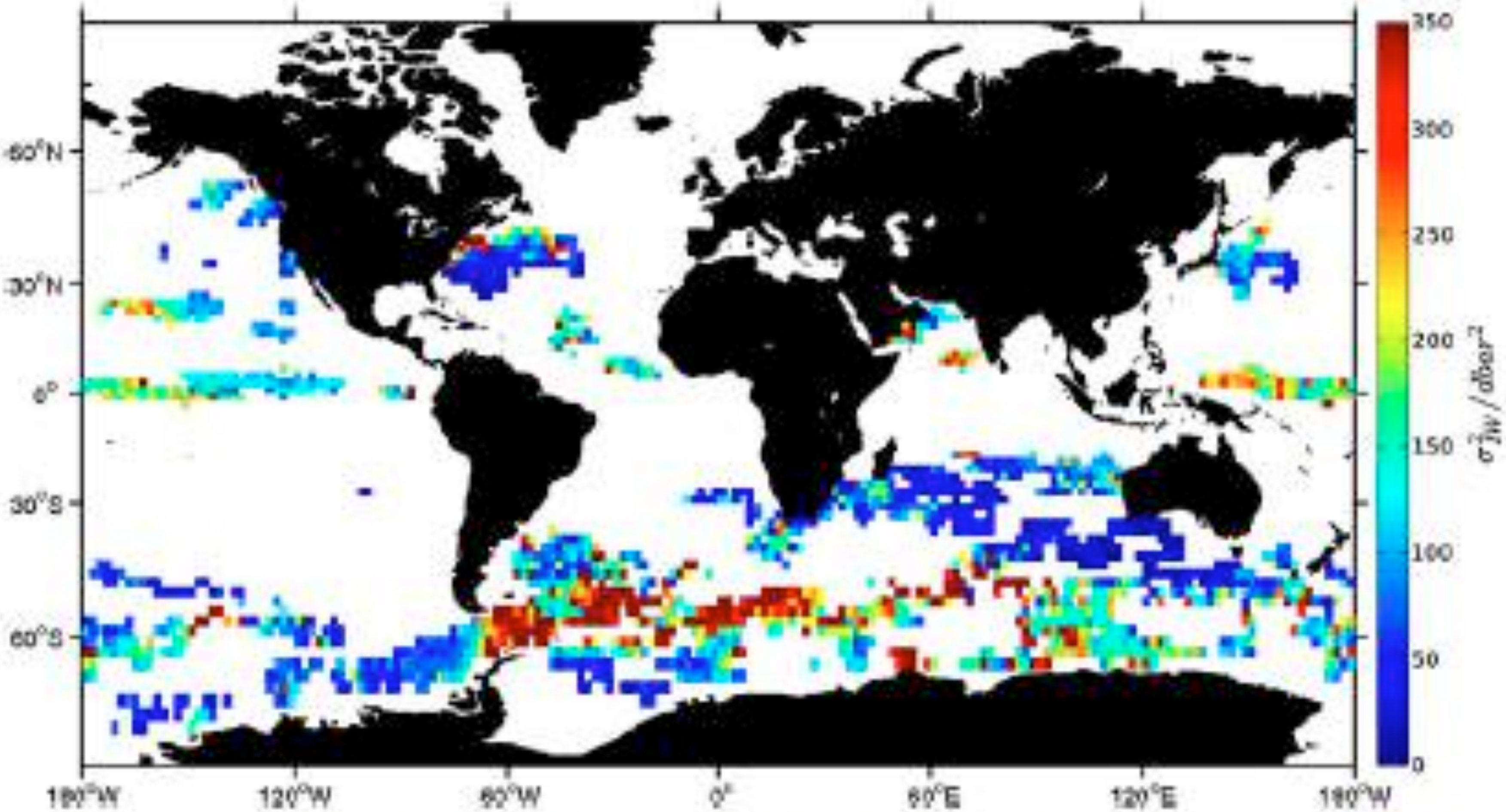
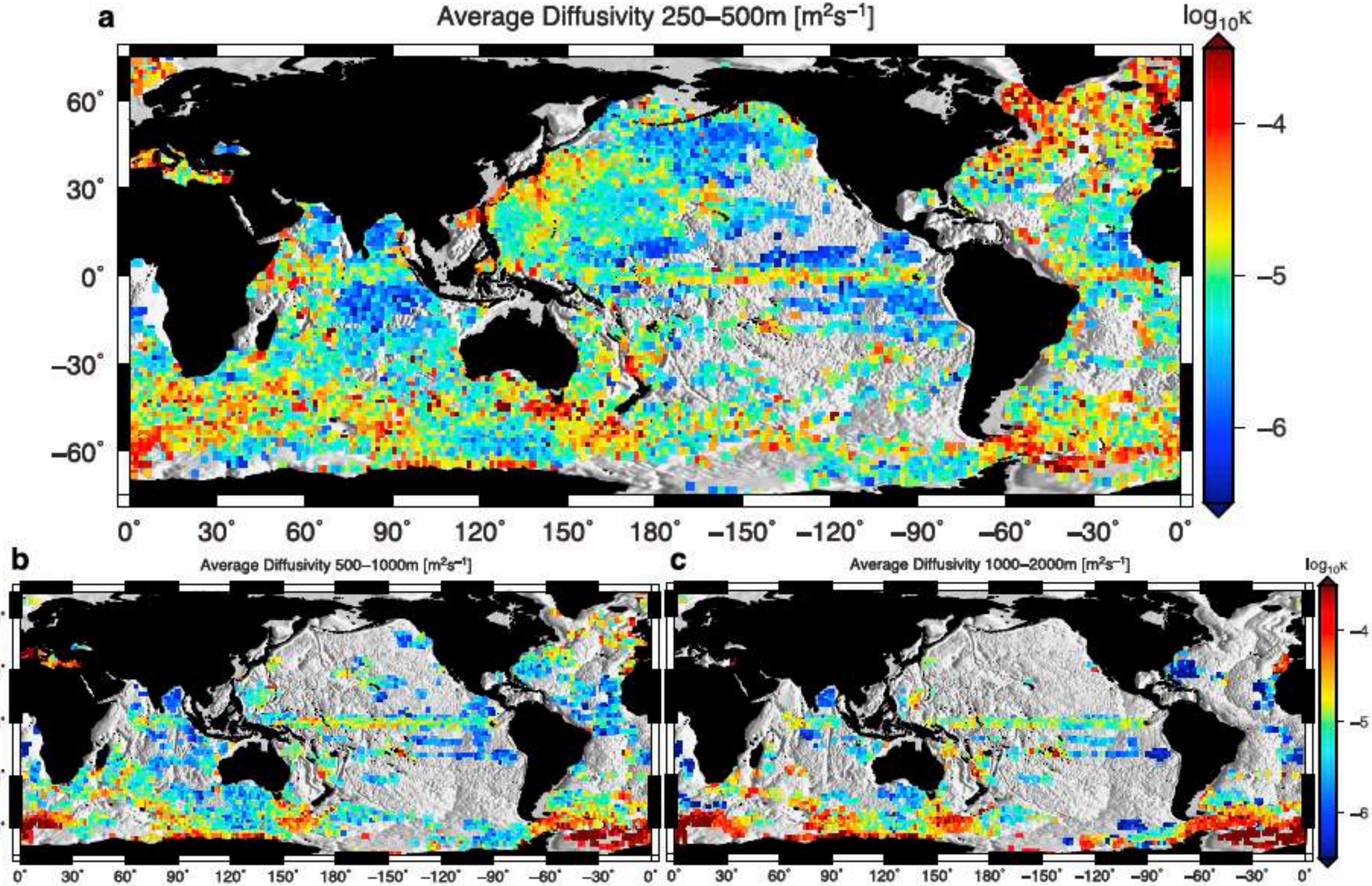


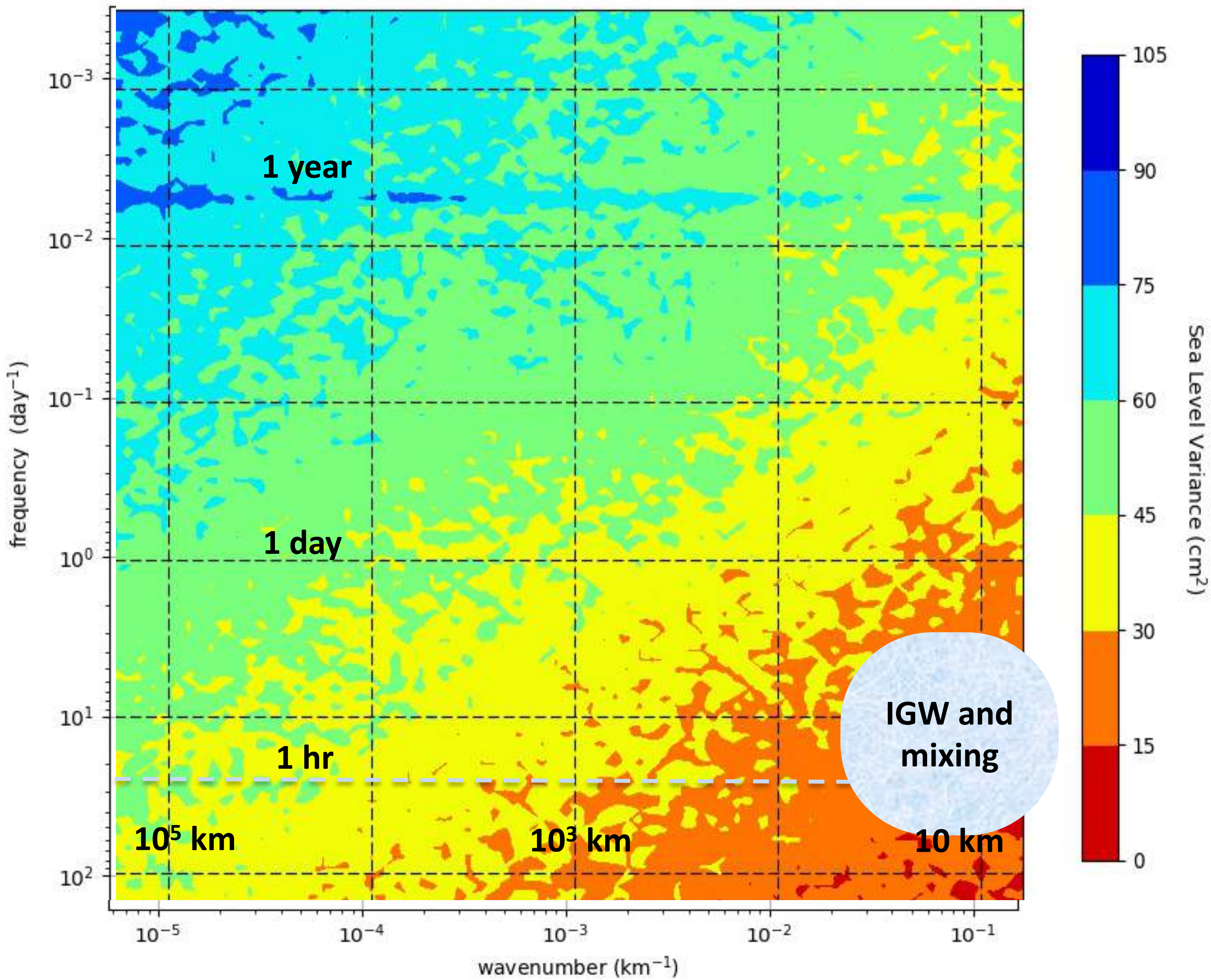
FIG. 11. Estimates of internal gravity wave vertical displacement variance from the 194 profiling floats used in this study. Values are averaged into 2° by 2° bins.

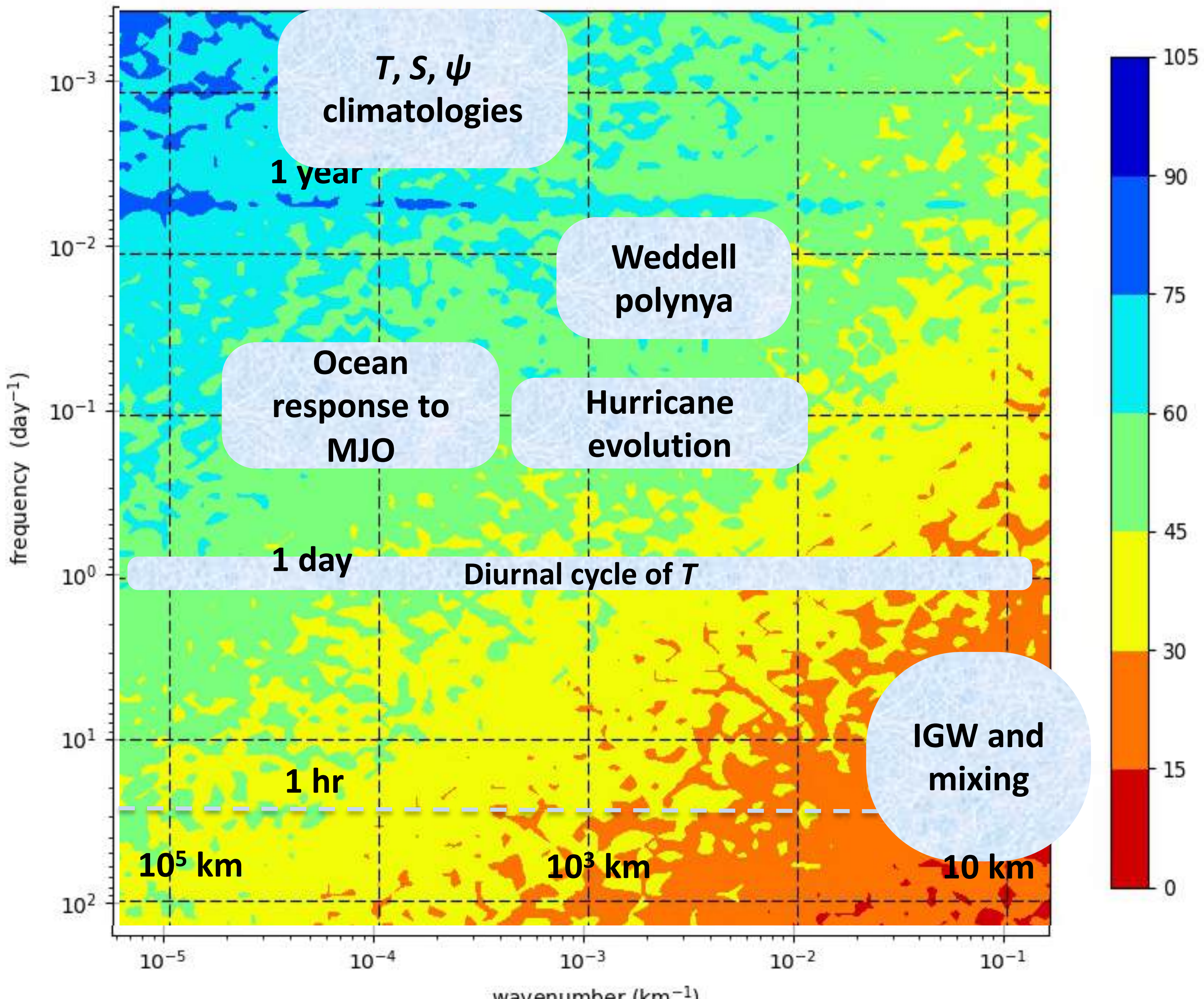
[Hennon et al., 2014]



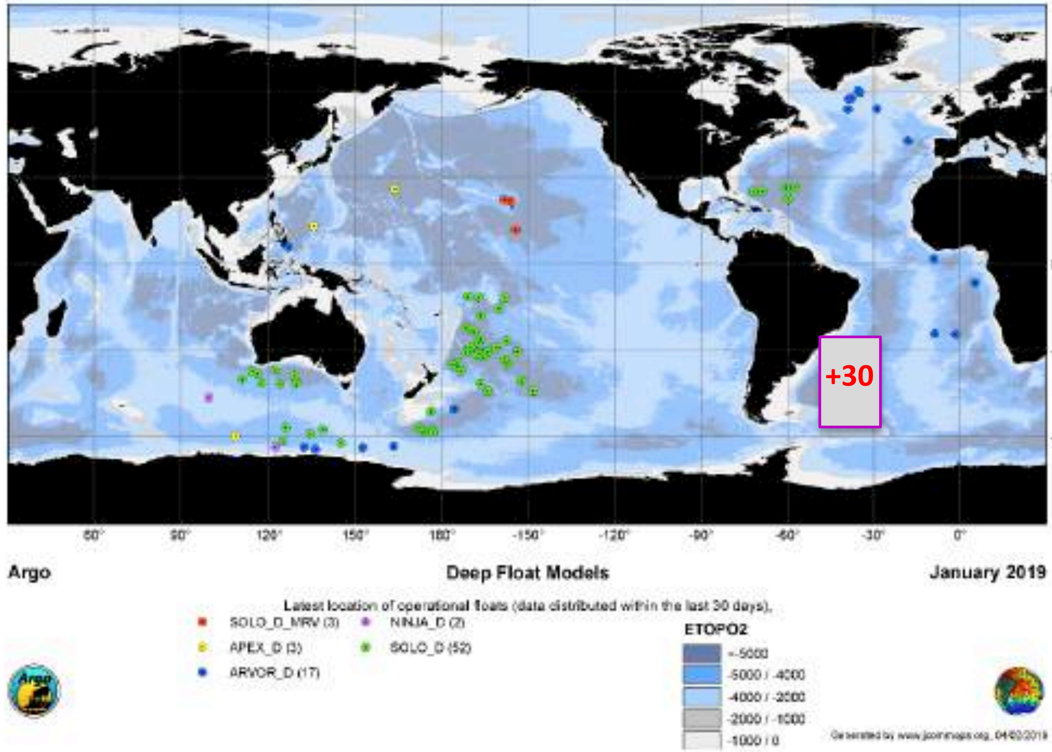
Vertical diffusivity κ_z estimated from high-resolution Argo profiles

[Whalen et al., 2012]

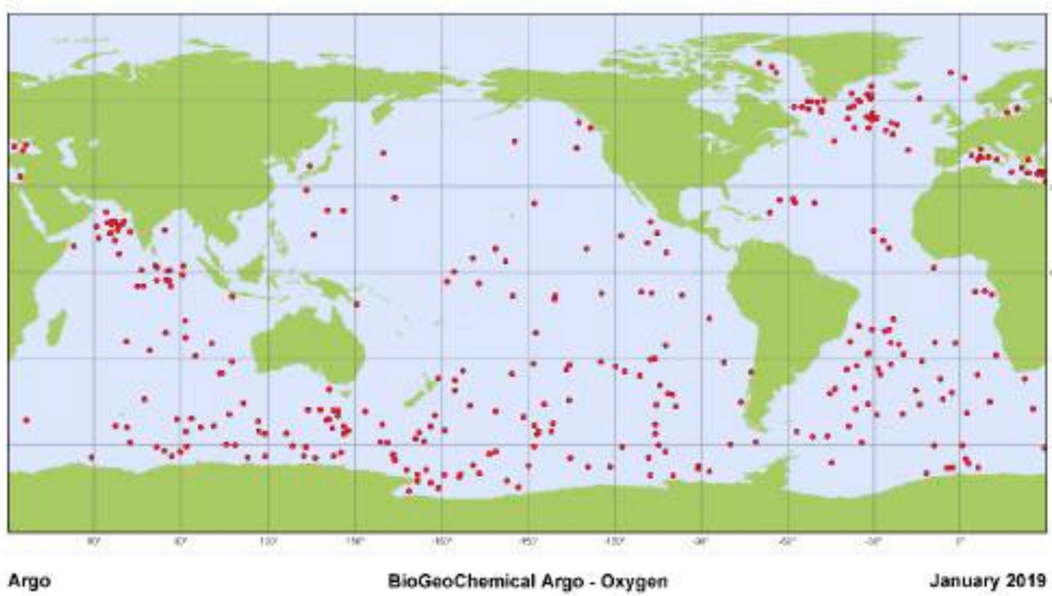

1 year
1 day
1 hr
IGW and mixing
10^5 km
10^3 km
10 km
10^{-3}
10^{-2}
10^{-1}
10^0
10^1
10^2
frequency (day^{-1})
10^{-5}
10^{-4}
10^{-3}
10^{-2}
10^{-1}
wavenumber (km^{-1})
105
90
75
60
45
30
15
0
Sea Level Variance (cm^2)



T, S, ψ climatologies
1 year
Weddell polynya
Ocean response to MJO
Hurricane evolution
1 day
Diurnal cycle of T
IGW and mixing
1 hr
10⁵ km
10³ km
10 km
frequency (day⁻¹)
10⁻³
10⁻²
10⁻¹
10⁰
10¹
10²
wavenumber (km⁻¹)
10⁻⁵
10⁻⁴
10⁻³
10⁻²
10⁻¹
Sea Level Variance (cm²)
105
90
75
60
45
30
15
0



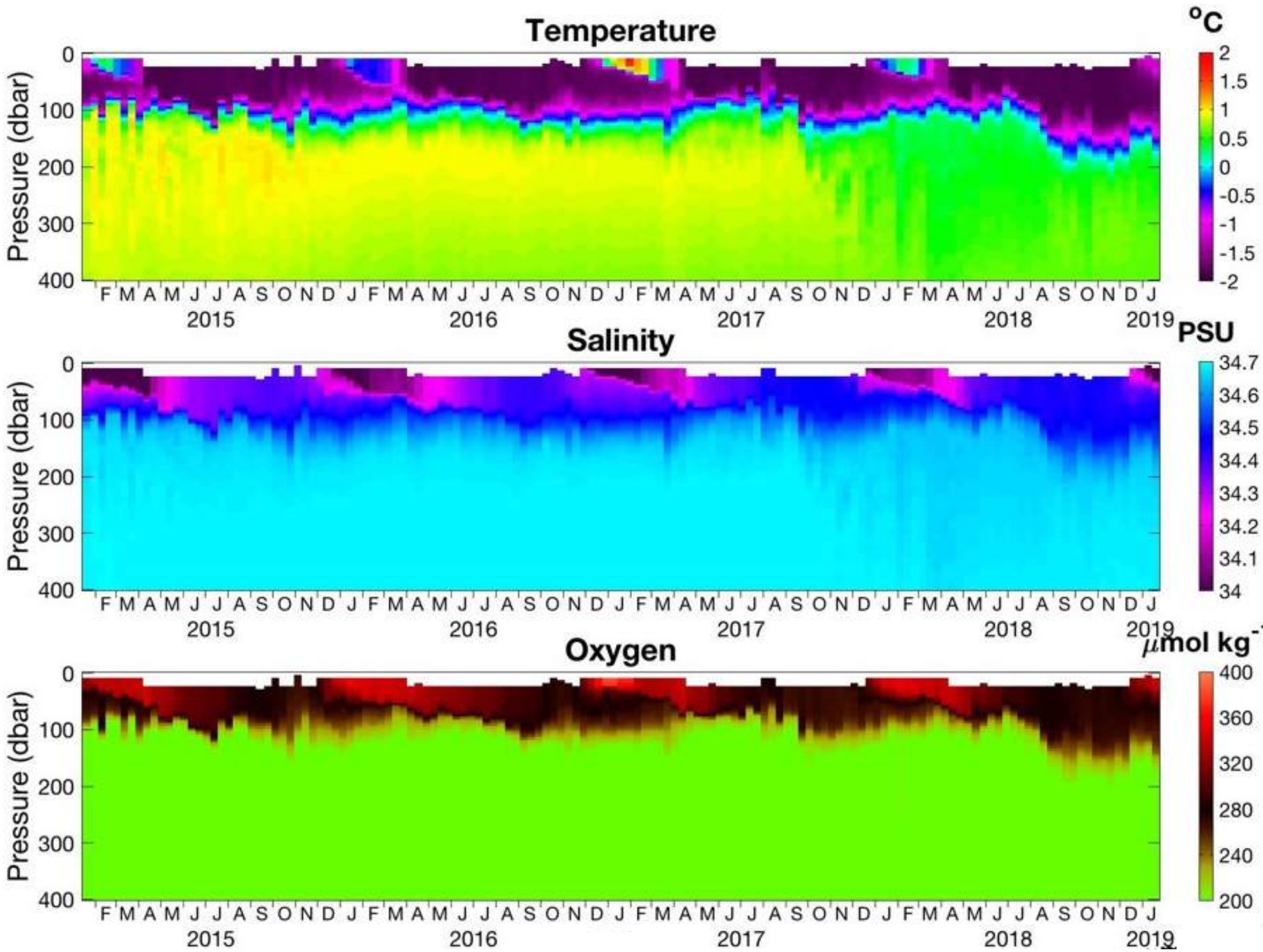
Deep Argo [presently 77 floats; long-term goal 1200]



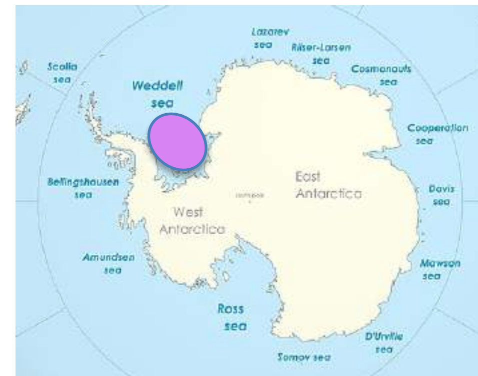
BGC-Argo [presently ≈ 300 floats; long-term goal 1000]

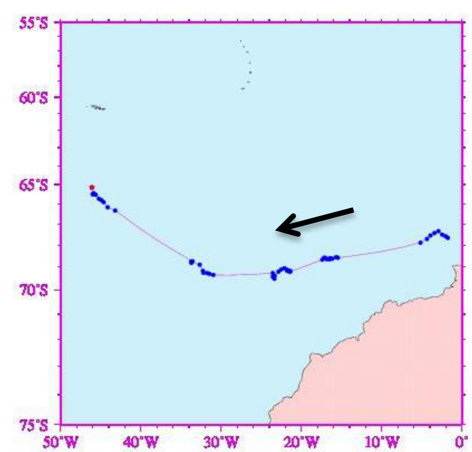
UW BGC-APEX Argo float

SIO Deep SOLO Argo float

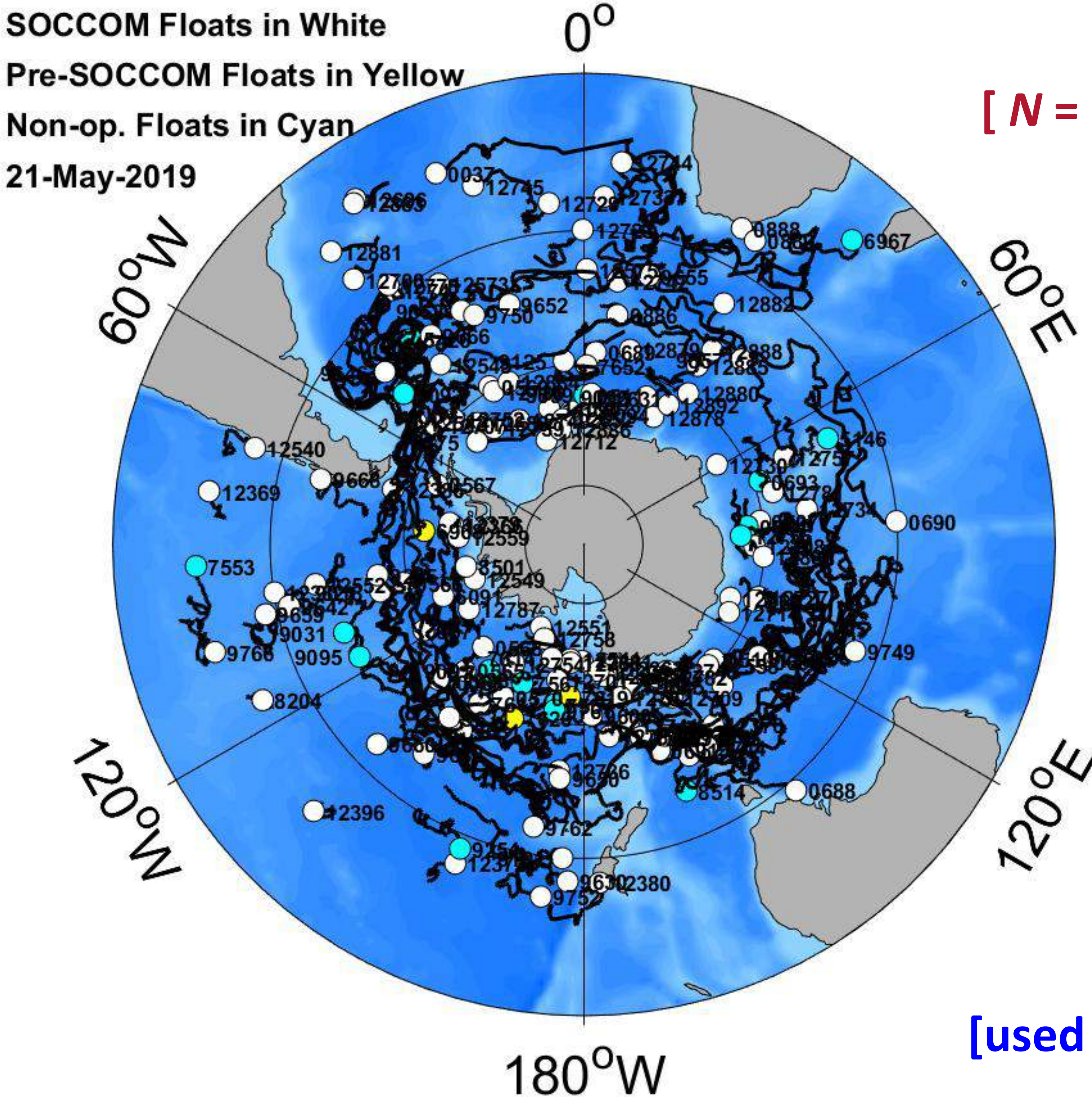


UW float 9275
WMO 5904472
1/18/15 – 3/12/19



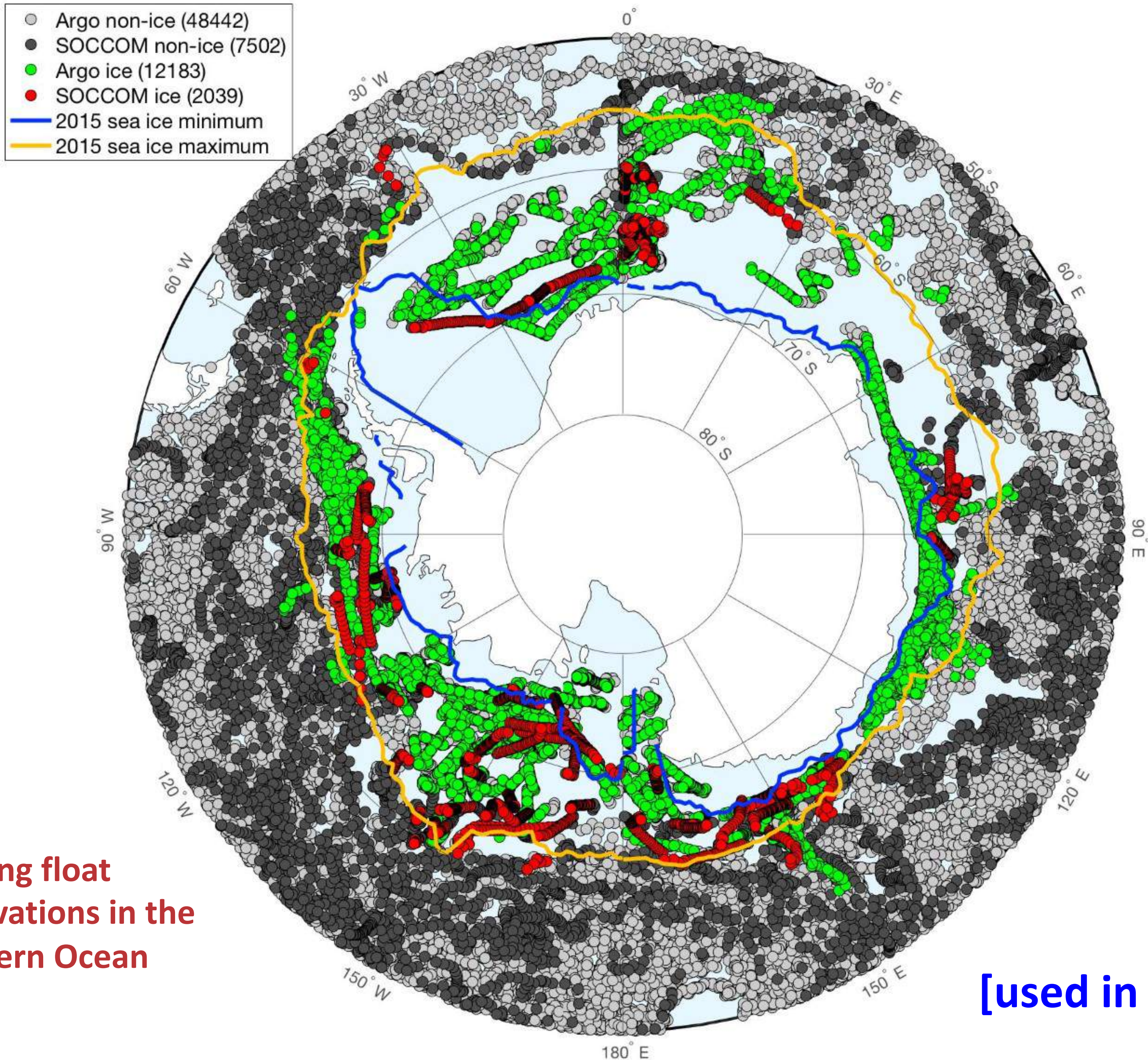


[also NO_3, pH, Chl, particulate backscatter]



[*N* = 134]

[used in SOSE]



Profiling float observations in the Southern Ocean

[used in SOSE]

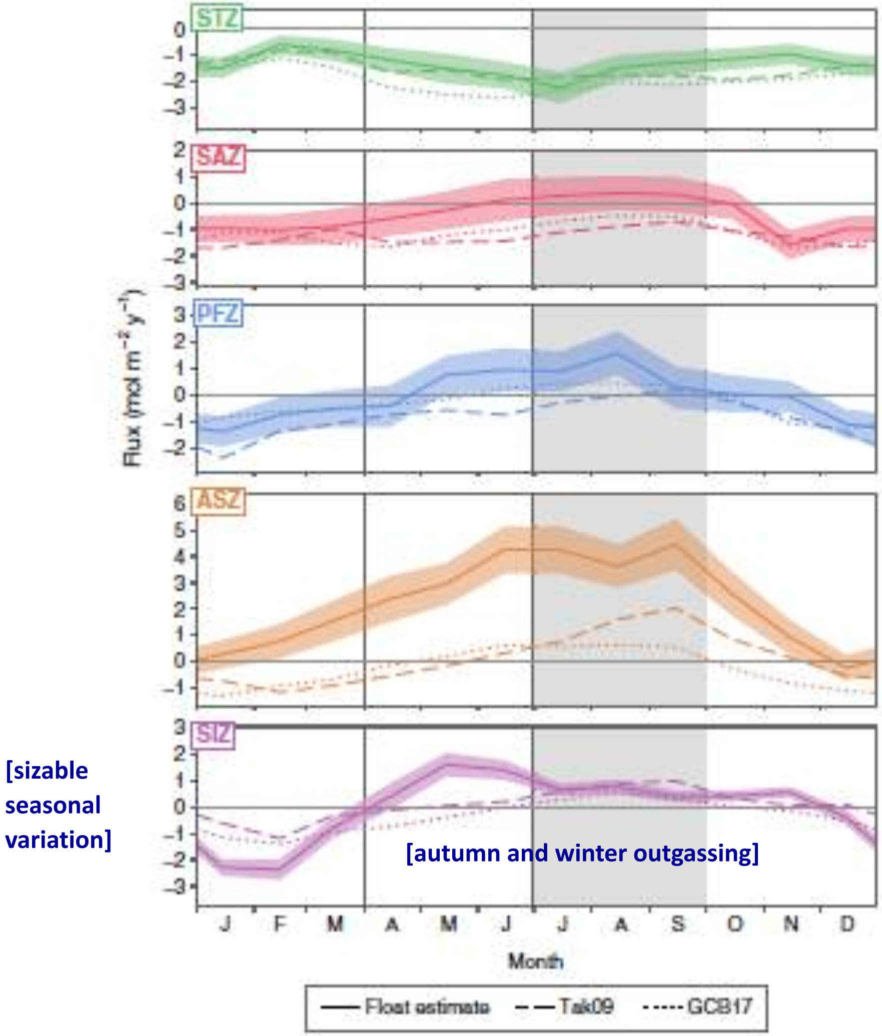


Figure 2. Monthly mean air-sea fluxes of CO_2 in each zone, computed from float observations, atmospheric CO_2 measurements, and wind speed estimates (solid lines). The shading represents ±1 standard error, calculated using a Monte Carlo simulation of the associated uncertainties (see Text S4). The mean monthly fluxes from Tak09 (dashed lines) and GCB17 (dotted lines) were calculated by sampling those estimates at the locations of the floats and averaging the resulting monthly mean fluxes as for the float data. Positive (negative) denotes flux out of (into) the ocean. Light gray vertical bar highlights winter months (July–September). STZ = Subtropical Zone; SAZ = Subantarctic Zone; PFZ = Polar Frontal Zone; ASZ = Antarctic-Southern Zone; SIZ = Seasonal Ice Zone.

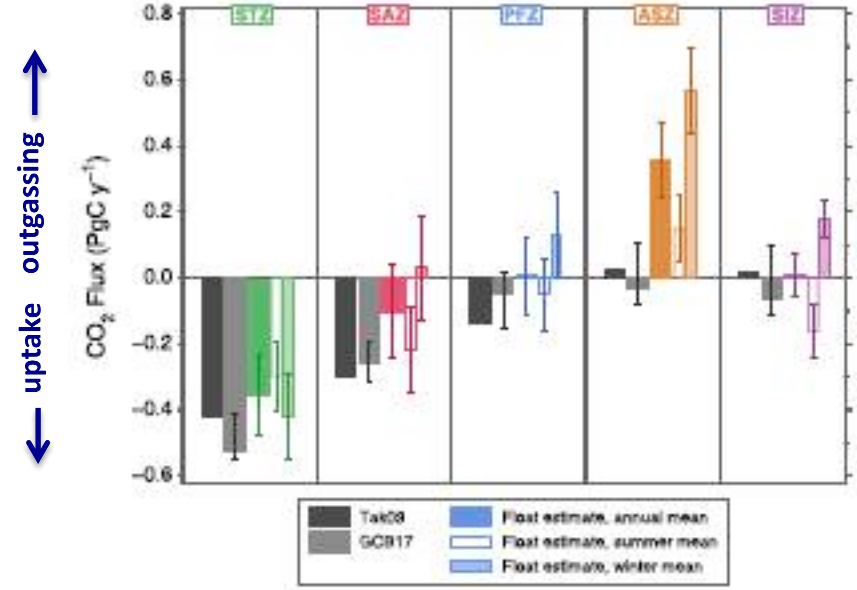


Figure 3. Annual net oceanic CO_2 flux (Pg C/year) estimated from float data (solid colors) and from two ship-based estimates, Tak09 (dark gray) and GCB17 (light gray), calculated by sampling the gridded estimates at the same locations as the floats. Uncertainty on the float estimates represents ±1 standard error, with contributions due to both spatiotemporal variability in the CO_2 flux and uncertainties in the data assessed with a Monte Carlo simulation (see Text S4). Error bars on the GCB17 data indicate the range of interannual variability across that 35-year estimate. The mean float-based estimates calculated for May–October (winter) and for November–April (summer) are shown by the narrow bars. Positive (negative) indicates net outgassing (uptake). STZ = Subtropical Zone; SAZ = Subantarctic Zone; PFZ = Polar Frontal Zone; ASZ = Antarctic-Southern Zone; SIZ = Seasonal Ice Zone.

Gray et al., 2018

Summary

- **In the roughly 20 years since the beginning of core-Argo, we have made substantial initial progress in beginning to meet the central goals to observe and understand the variability of heat and freshwater in the ocean on climate scales. This insight will only grow as the project continues.**

- **Argo has managed to sample a substantial portion of the space-time spectrum of variability in the ocean, although this was perhaps not anticipated by most of the designers of the project. There remain large and potentially interesting portions of the space-time spectrum that have not be sampled.**

- **In another decade or two, it is likely that such results from core-Argo will be accompanied by similar new insight from deep Argo and BGC-Argo, which are at a similar stage of development to core-Argo 20 years ago.**