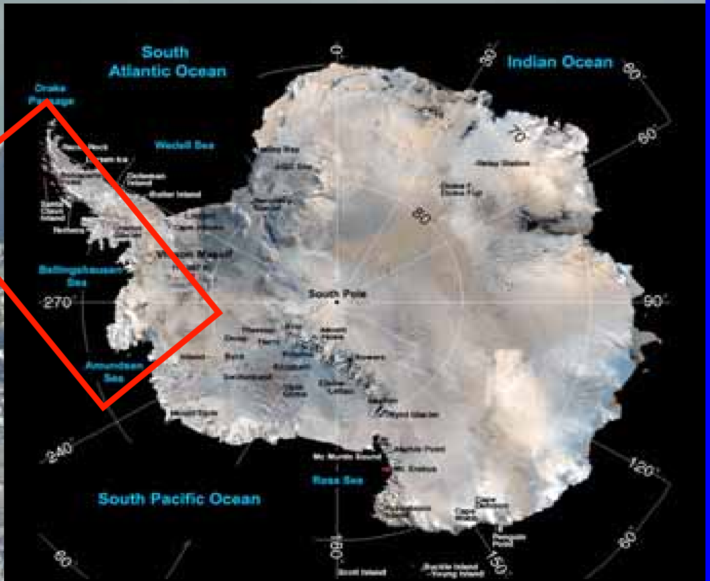
Increased ocean heat along the continental margin of west Antarctica

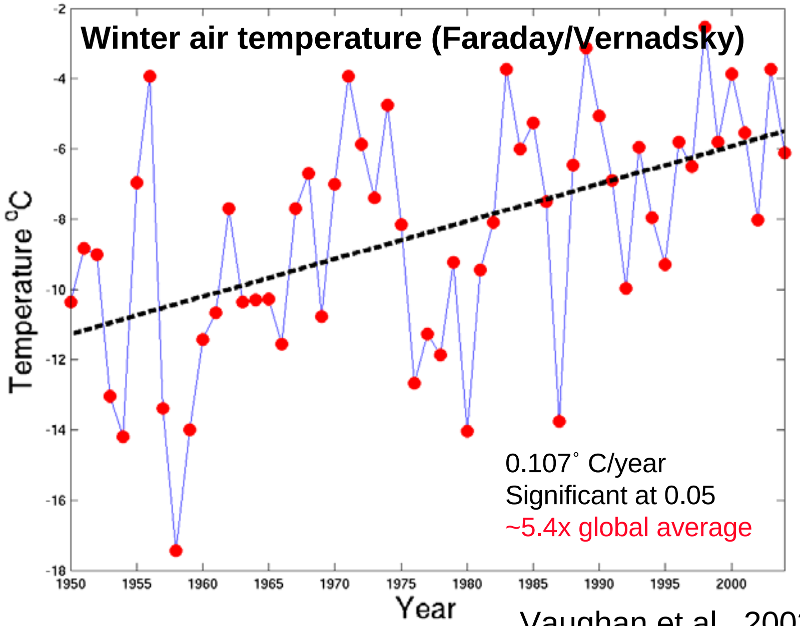


mstecker.com/pages/antsatmap.htm

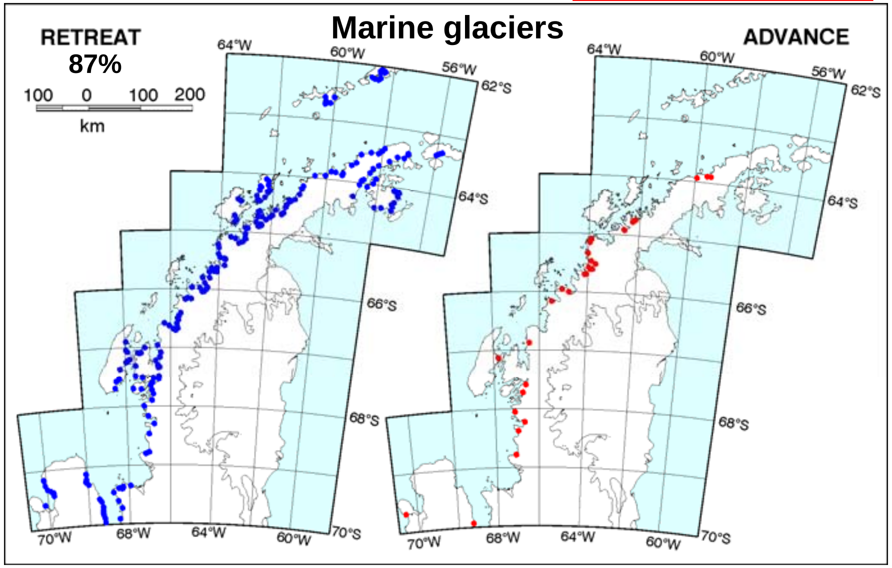
Douglas G. Martinson
Lamont-Doherty Earth Observatory
Columbia University
dgm@ldeo.columbia.edu

Photo: Dr. R.C. Smith, Sep. 2001

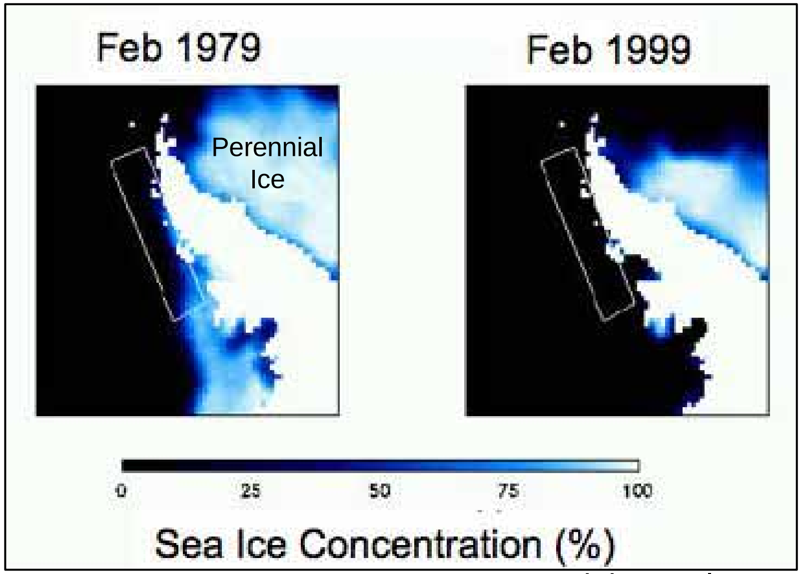
Dramatic change



Vaughan et al., 2003

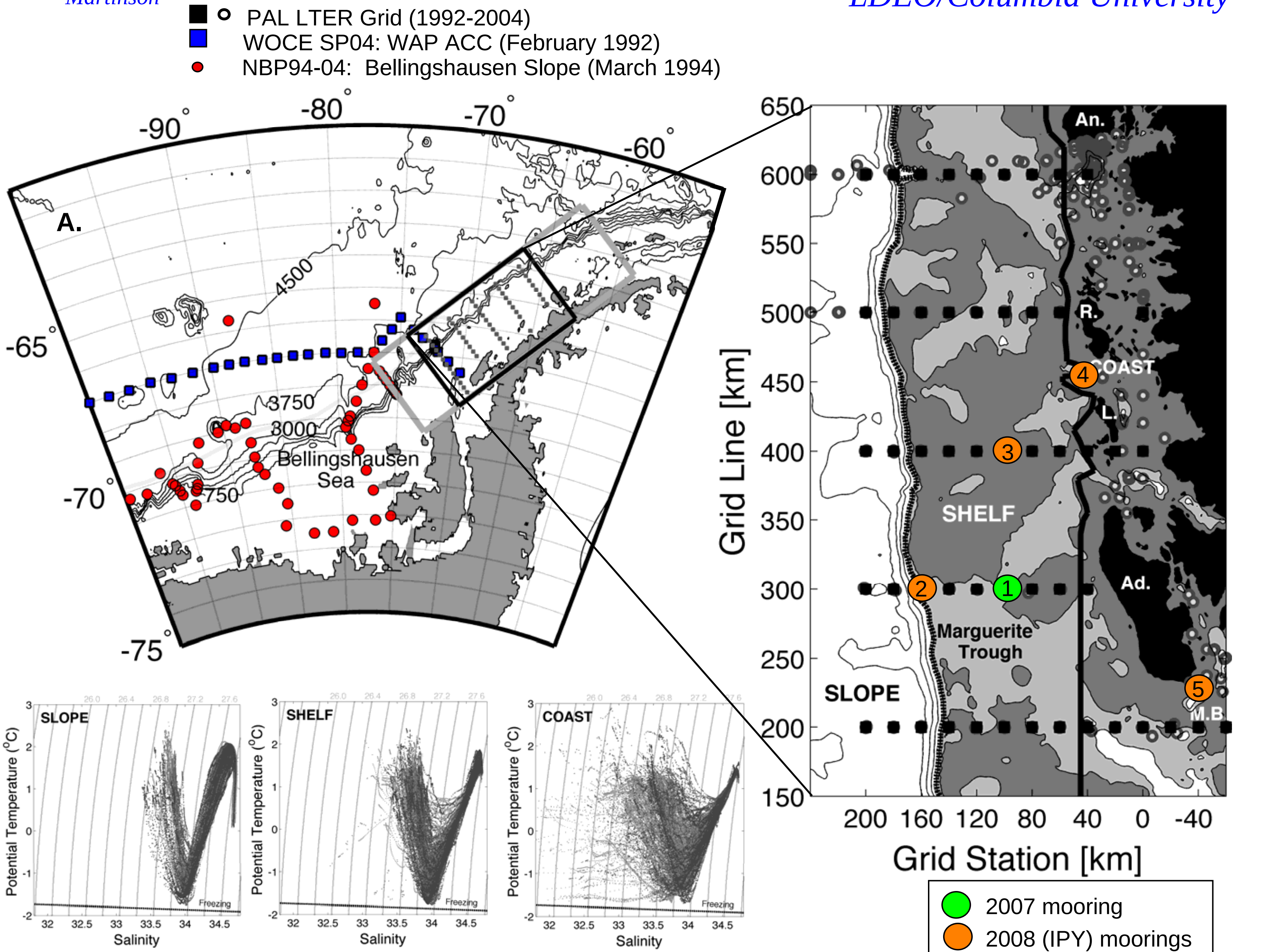


Cook et al., 2005



Stammerjohn et al., 2007

Fraser et al., 2008

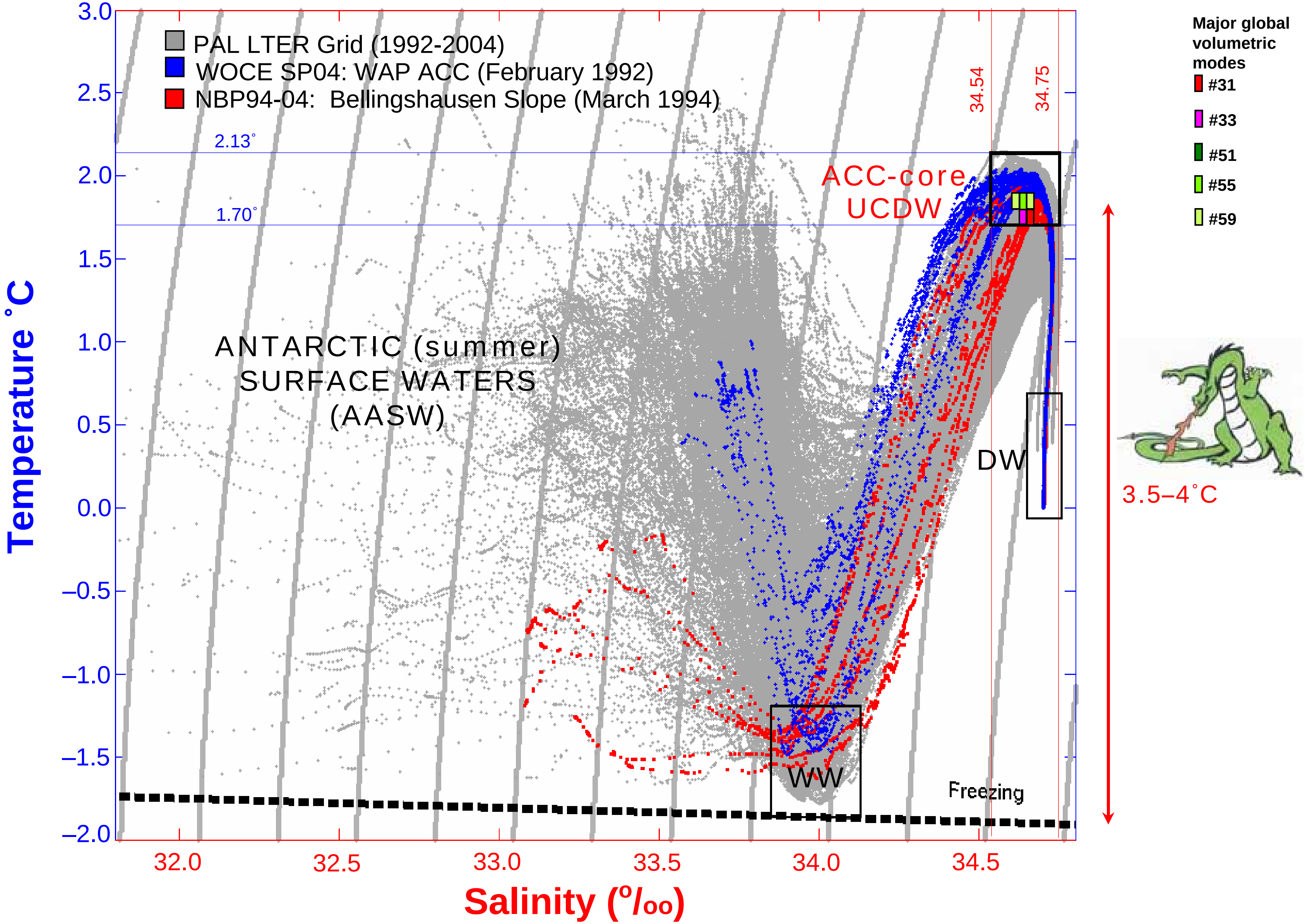

PAL LTER Grid (1992-2004)
WOCE SP04: WAP ACC (February 1992)
NBP94-04: Bellingshausen Slope (March 1994)
A.
-90°
-80°
-70°
-60°
-65°
-70°
-75°
4500
3750
3000
750
Bellingshausen Sea
Grid Line [km]
Grid Station [km]
An.
R.
COAST
L.
SHELF
Ad.
Marguerite Trough
SLOPE
M.B.
2007 mooring
2008 (IPY) moorings
SLOPE
SHELF
COAST
Potential Temperature (°C)
Salinity
Freezing

Martinson
LDEO/Columbia University

Source of *winter* heat

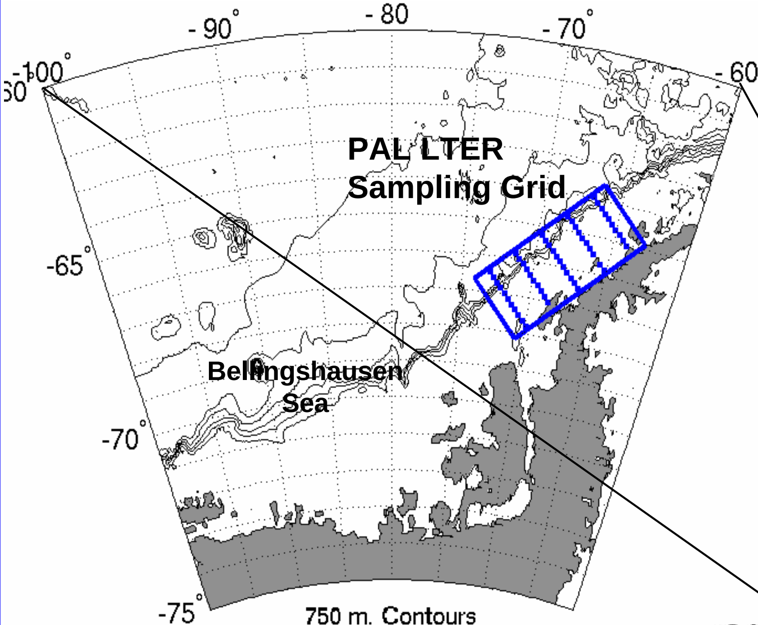
Source of heat

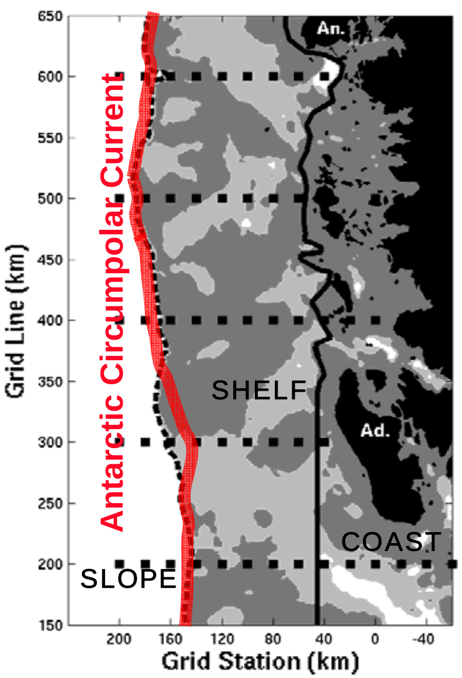
(atmosphere is frigid & sun near horizon; suggests ocean)

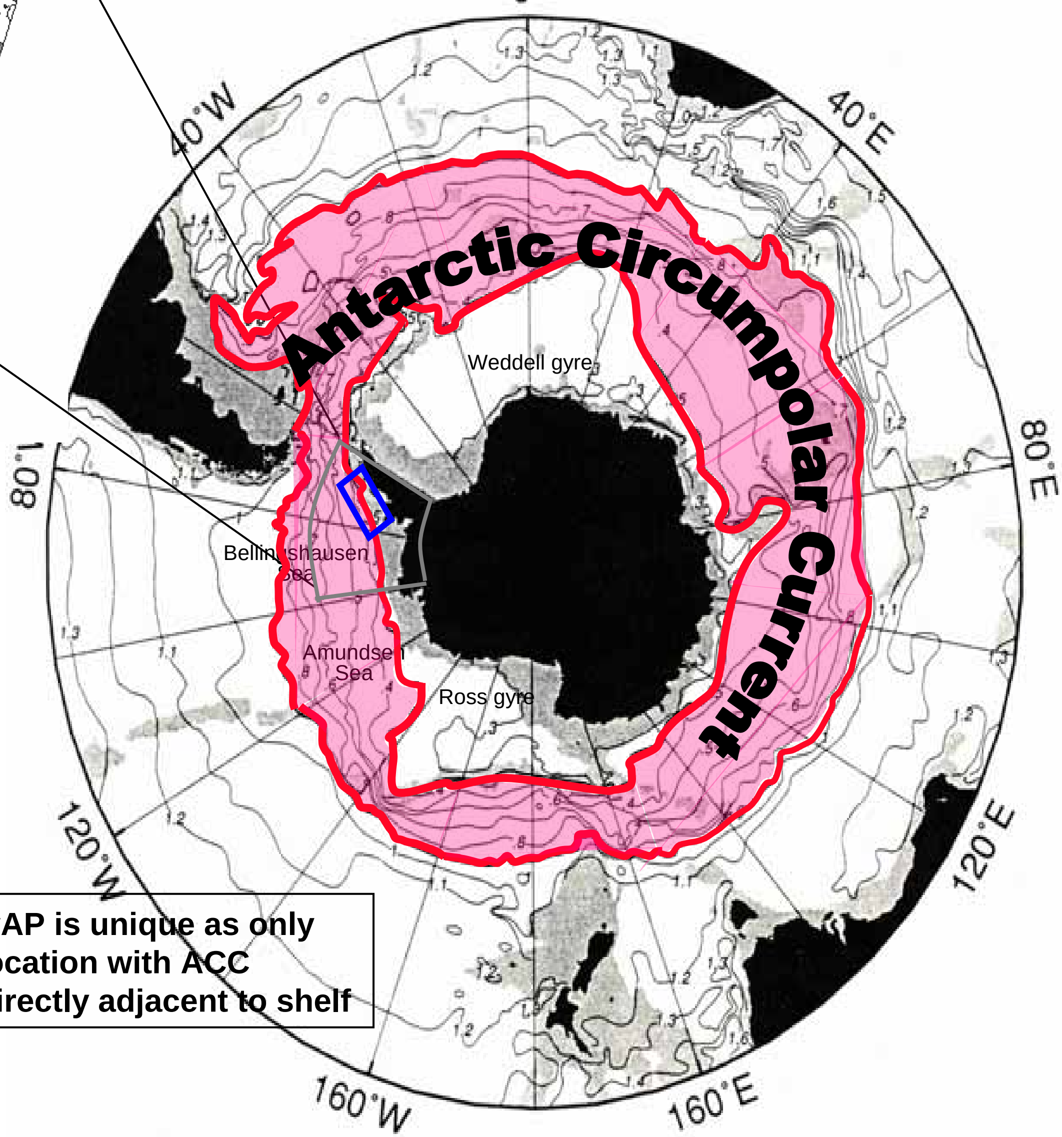


Proximity of heat

The Southern Ocean

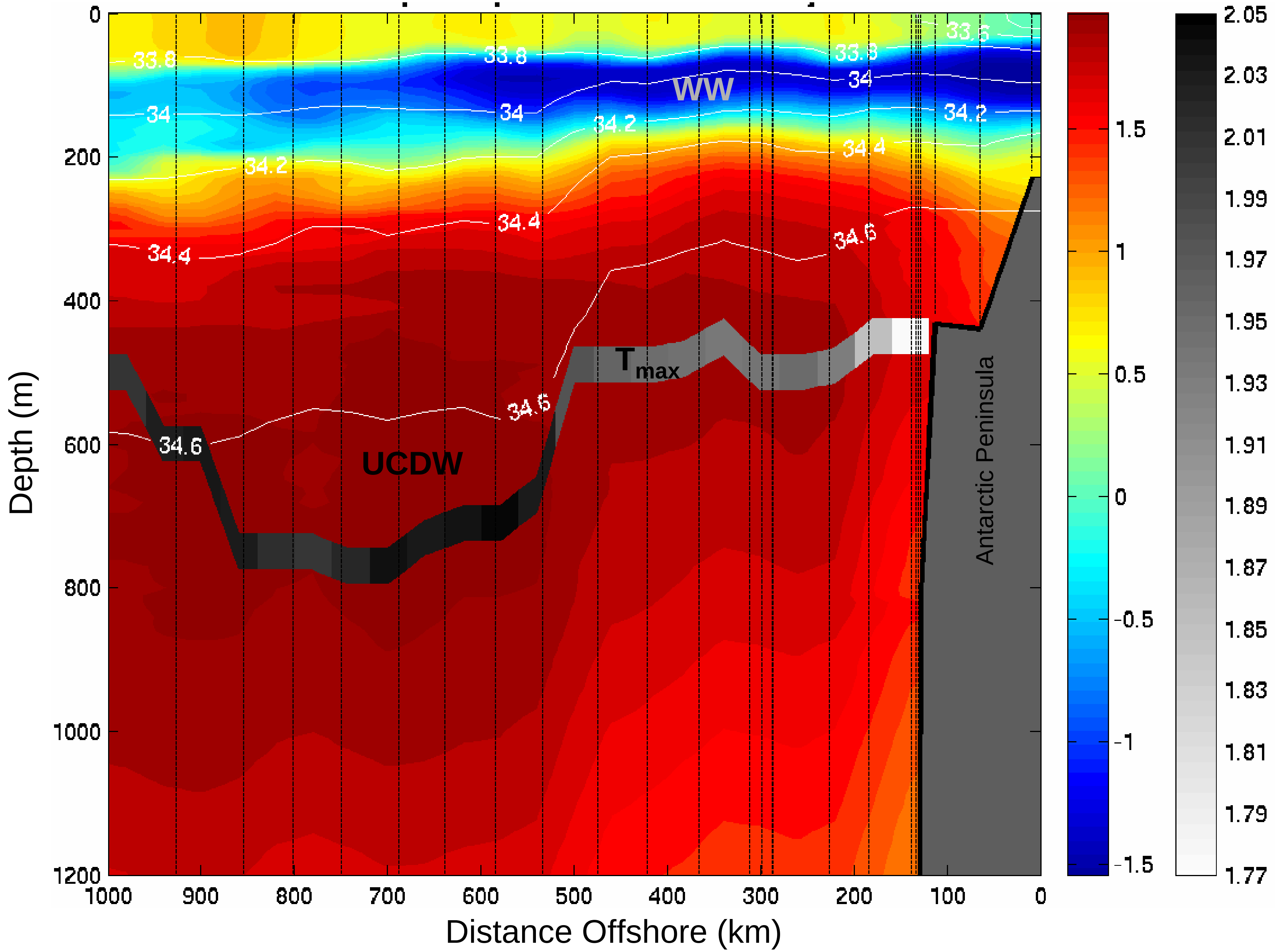




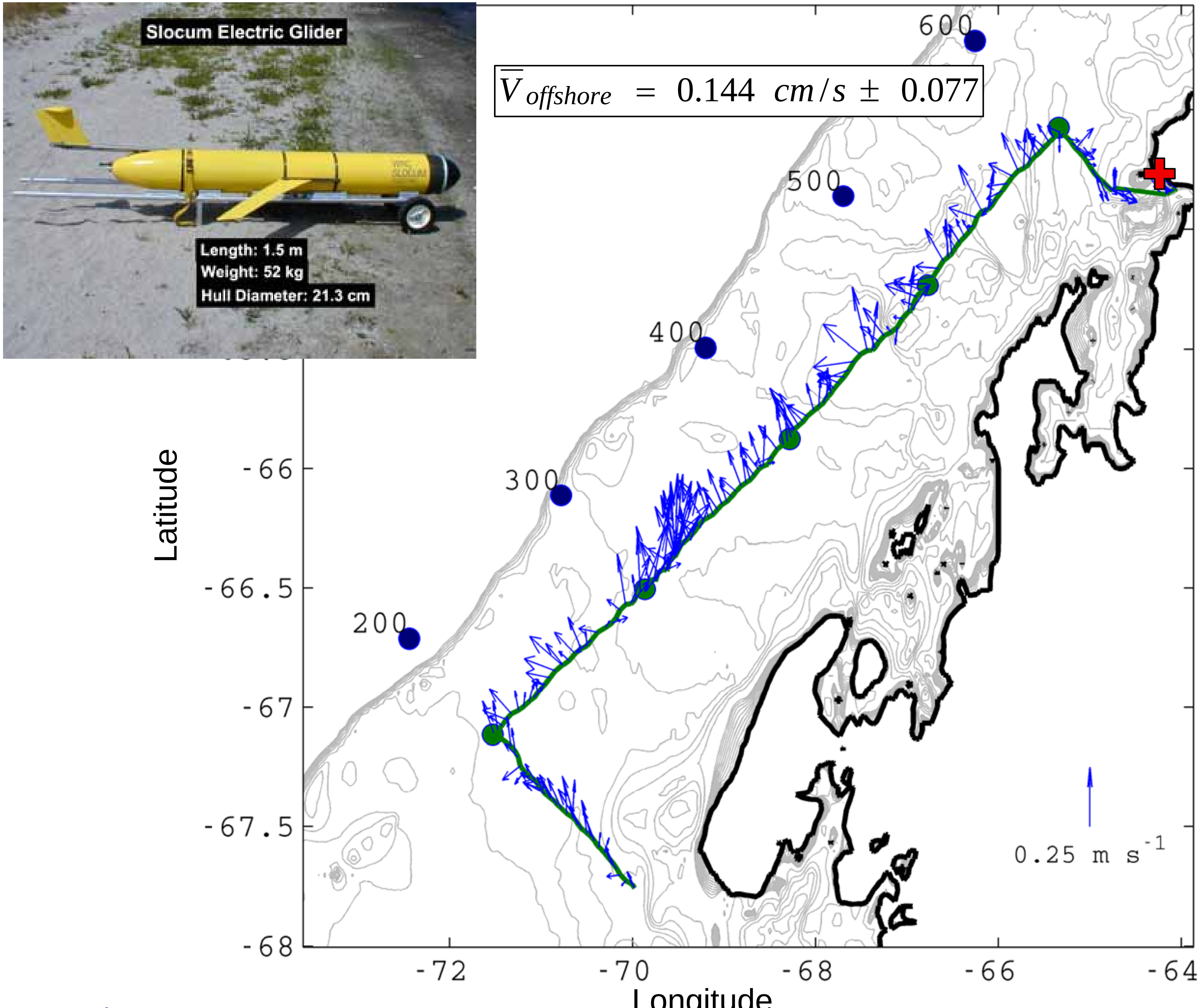


wAP is unique as only location with ACC directly adjacent to shelf

Current dynamics raises warm water to near-surface

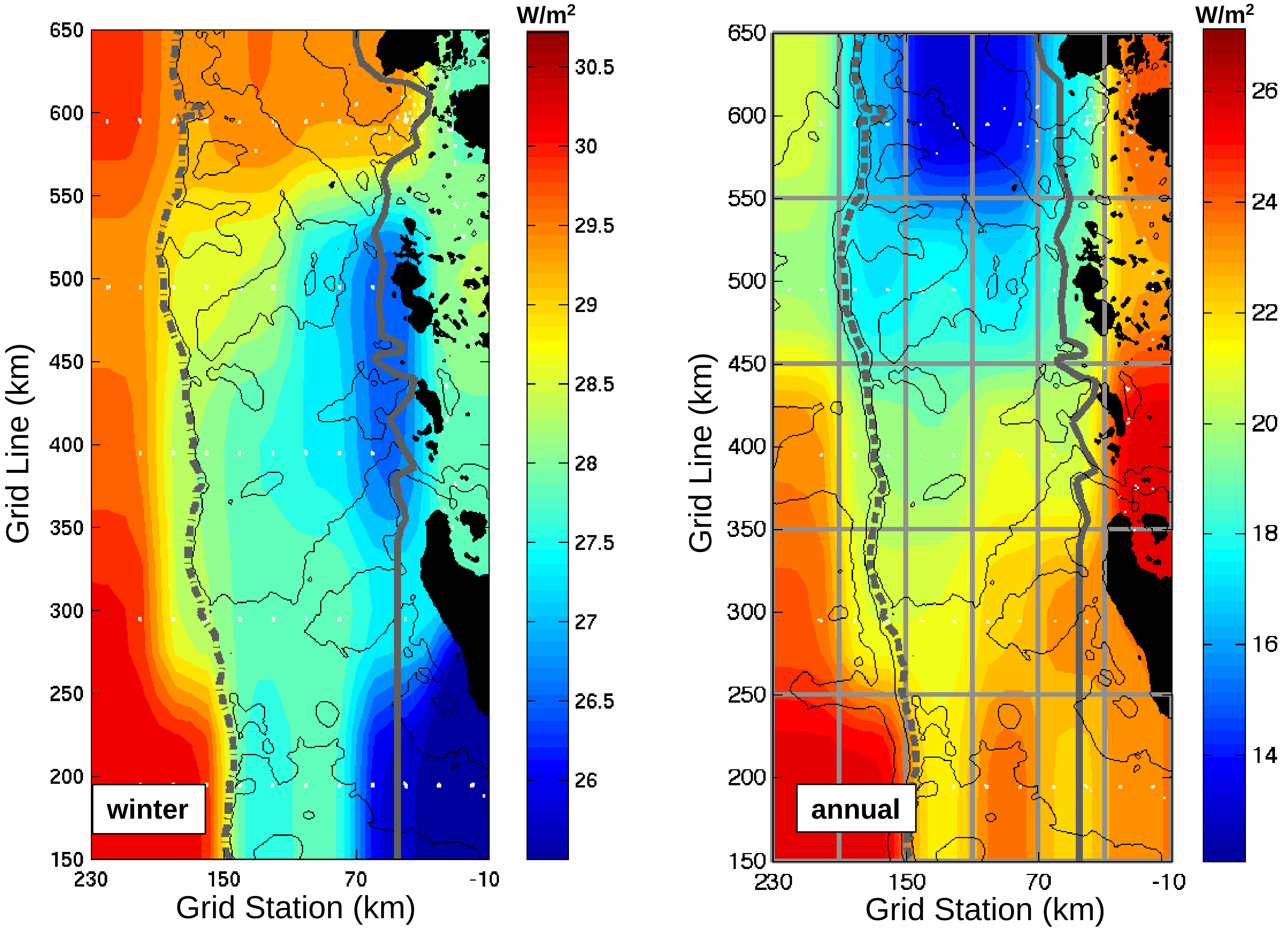


delivery

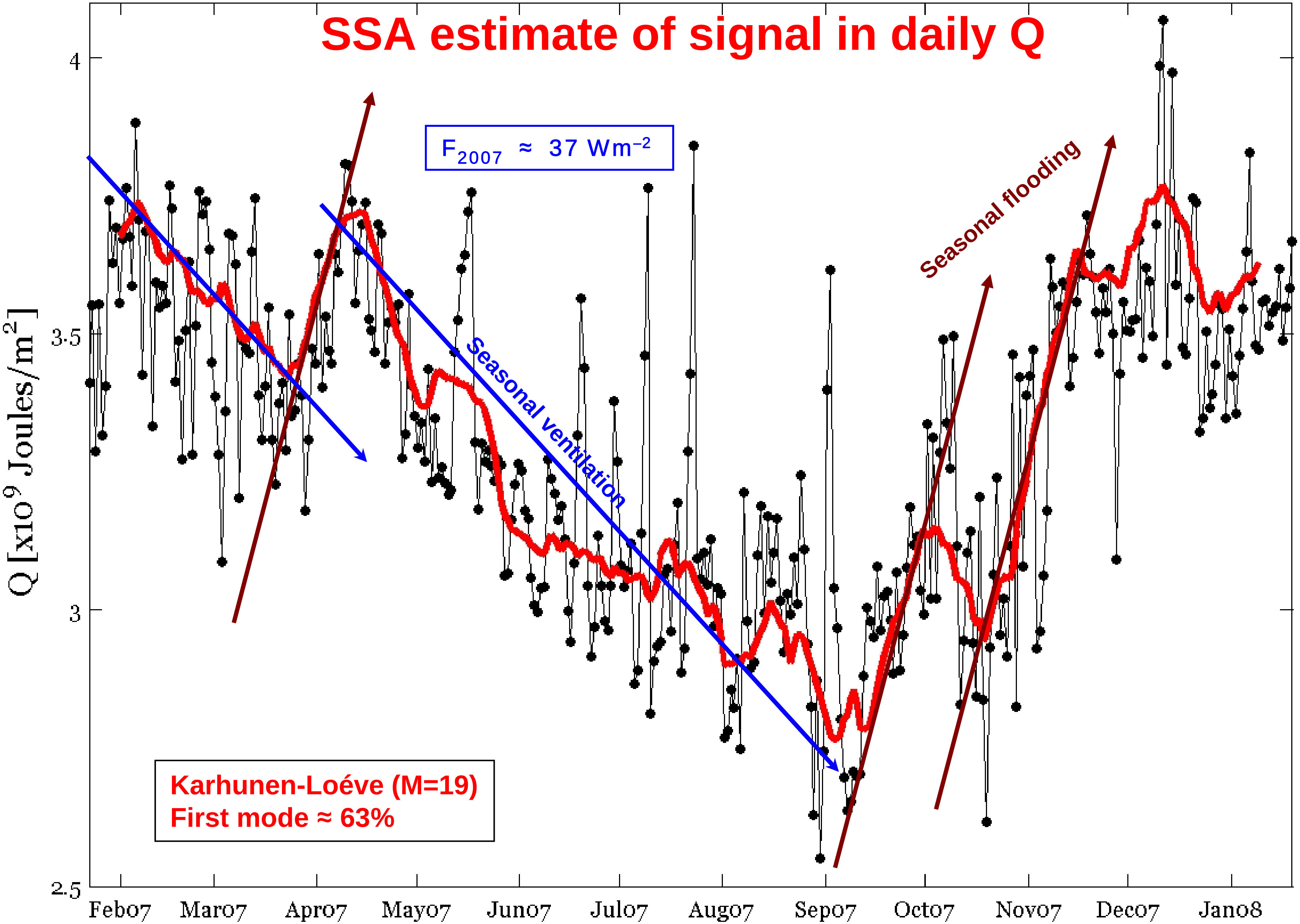

Slocum Electric Glider
Length: 1.5 m
Weight: 52 kg
Hull Diameter: 21.3 cm
$\overline{V}_{offshore} = 0.144\ cm/s \pm 0.077$
600
500
400
300
200
0.25 m s^-1
-66
-66.5
-67
-67.5
-68
-72
-70
-68
-66
-64
Latitude
Longitude

Bulk Property winter and annual average heat flux

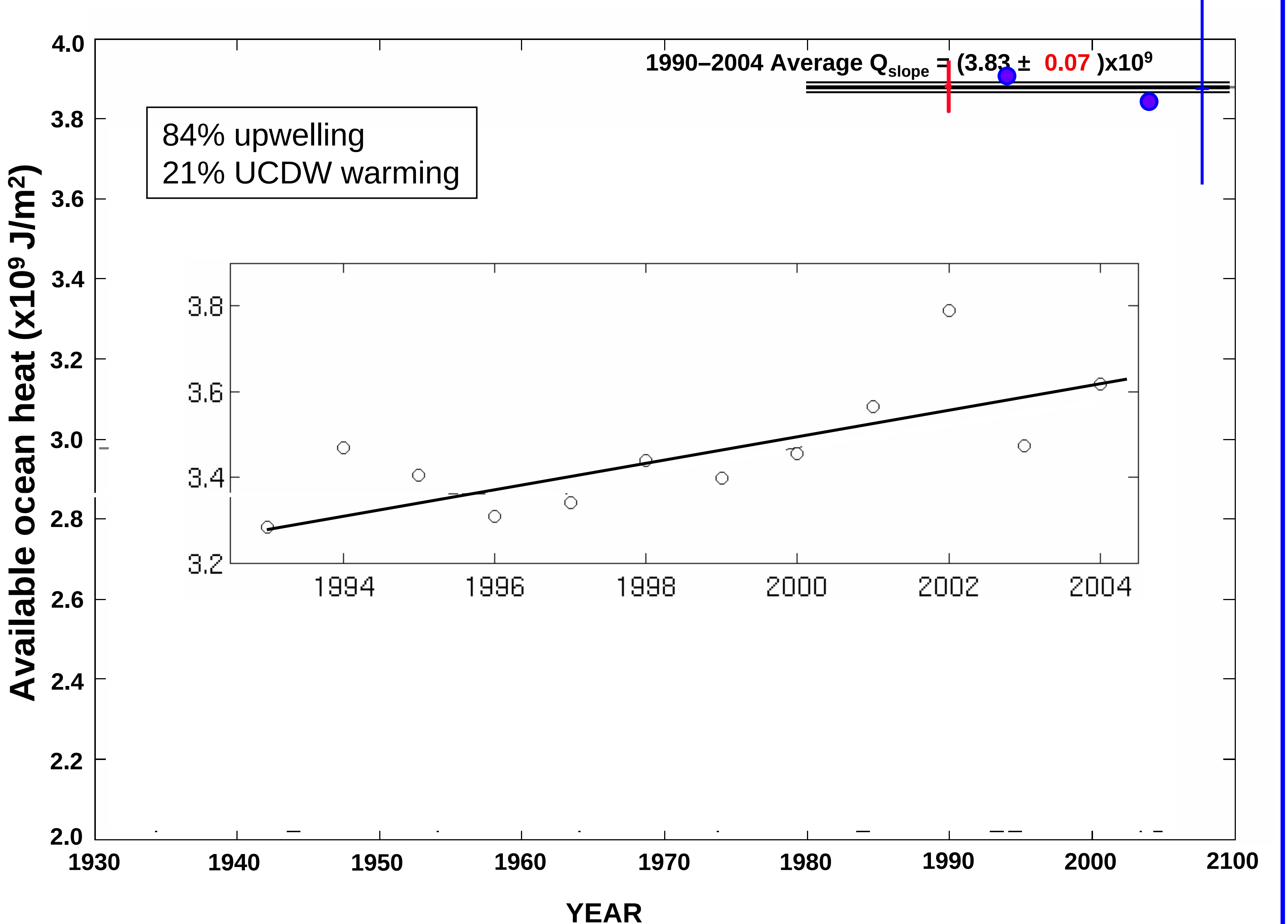
Heat flux



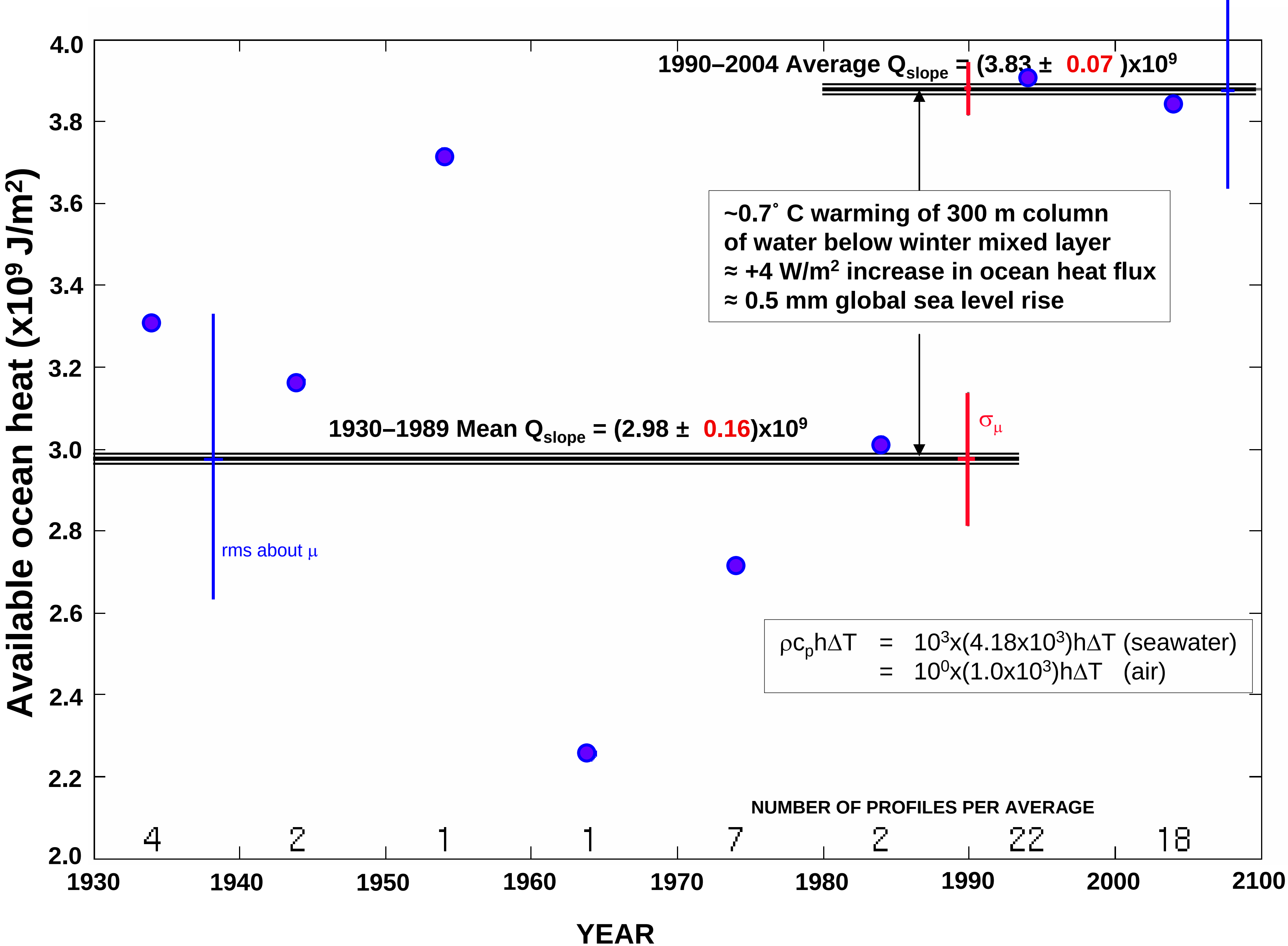
SSA estimate of signal in daily Q



Change in ocean heat



Change in ocean heat



Conclusions:

- **WAP region dominated by ACC/UCDW water along slope delivering heat and nutrients to WAP continental shelf**

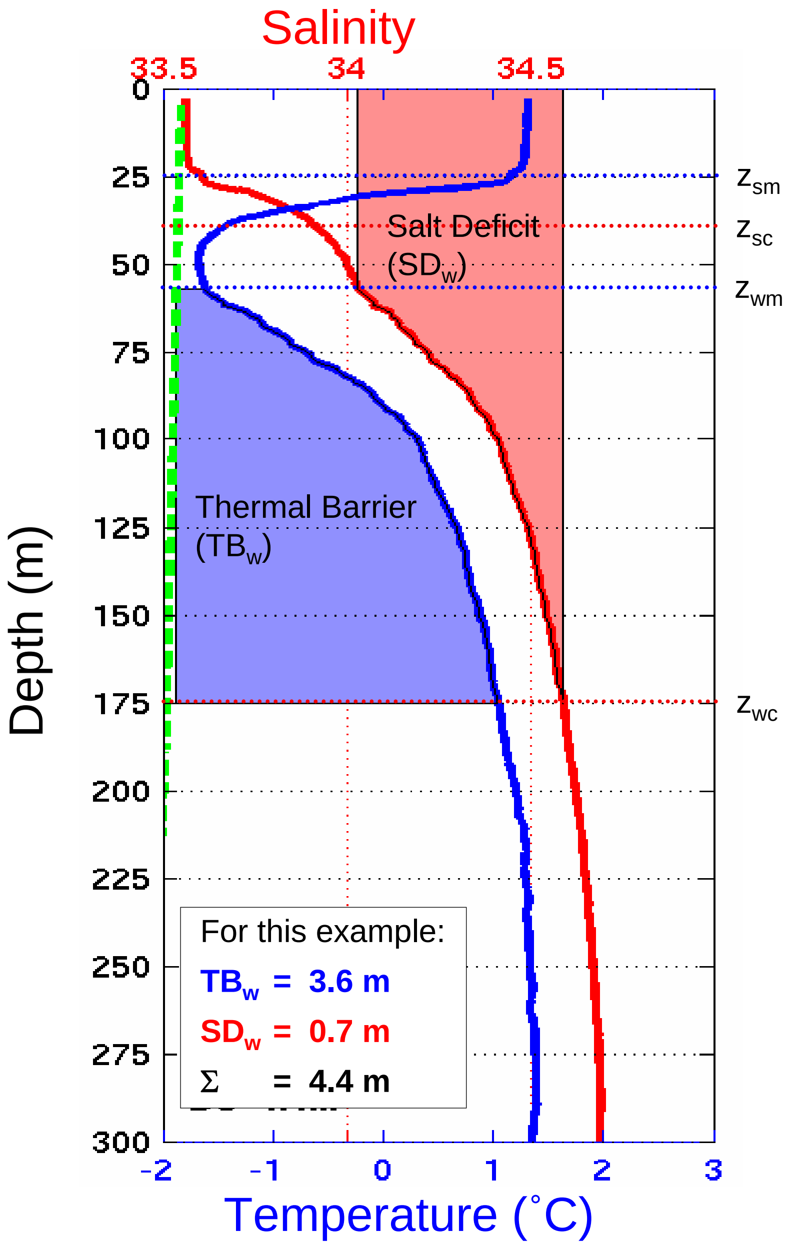
- **UCDW floods shelf from dynamical forcing (upwelling) on a regular *seasonal* basis (for 2007)**
    - Entire deep water column is advected onto shelf in:
        - Summer/Autumn transition (April)
        - Winter's end and Spring/Summer transition
    - Slope waters do enter canyons, but flooding is *not* from overflow of canyons onto shelf

Open Question:

- **Dramatic jump in late eighties heat content available to shelf, due to:**
    - Extrapolar ocean warming finally advected to WAP, and/or
    - Change in westerlies driving different filament(s) of ACC onto shelf, or
    - Bad statistics?

So, Here We Are

"I don't know anything about global warming, but these ice cubes are melting like crazy."



$F_{DT} = k_z \rho c_p \nabla T$ (diffusive heat flux)

$\Sigma = TB_w + SD_w$ **(bulk stability)**

$F_{ET} = (TB_w/\Sigma) F_L$ (entrainment heat flux)

$F_L = (F_{air} - F_L)$ (latent heat flux)

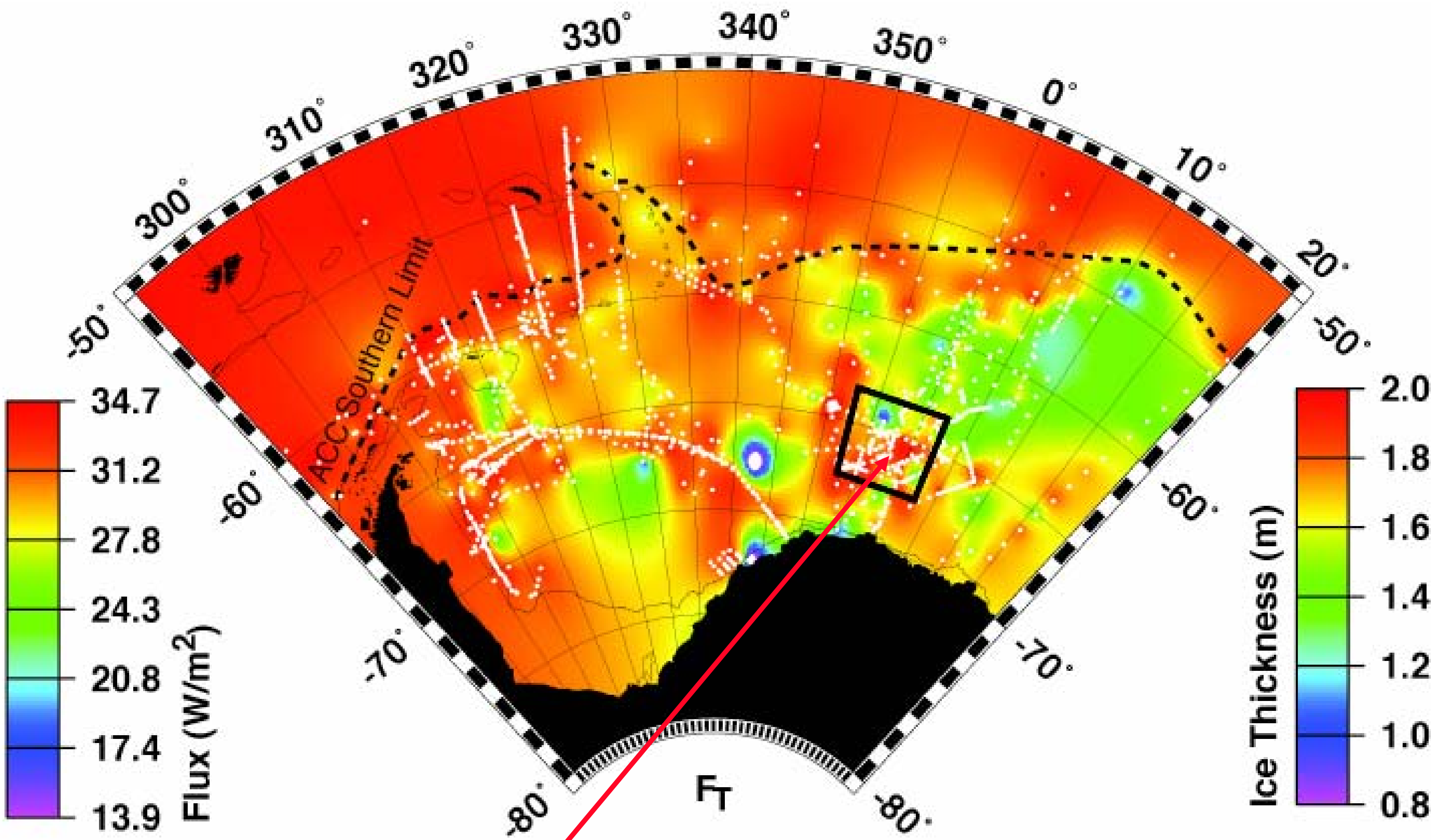
$F_T = F_{DT} + F_{ET}$ **(total winter heat flux)**

$$SD_S = \left(\frac{1}{\sigma_i}\right)\int_0^{z_{wm}} (S_{wm} - S)\,dz$$

$$TB_W = \left(\frac{\rho_w c_p}{\rho_i L_i}\right)\left[\int_{z_{wm}}^{z_{wc}} \left(T - T_f\right) dz\right]$$

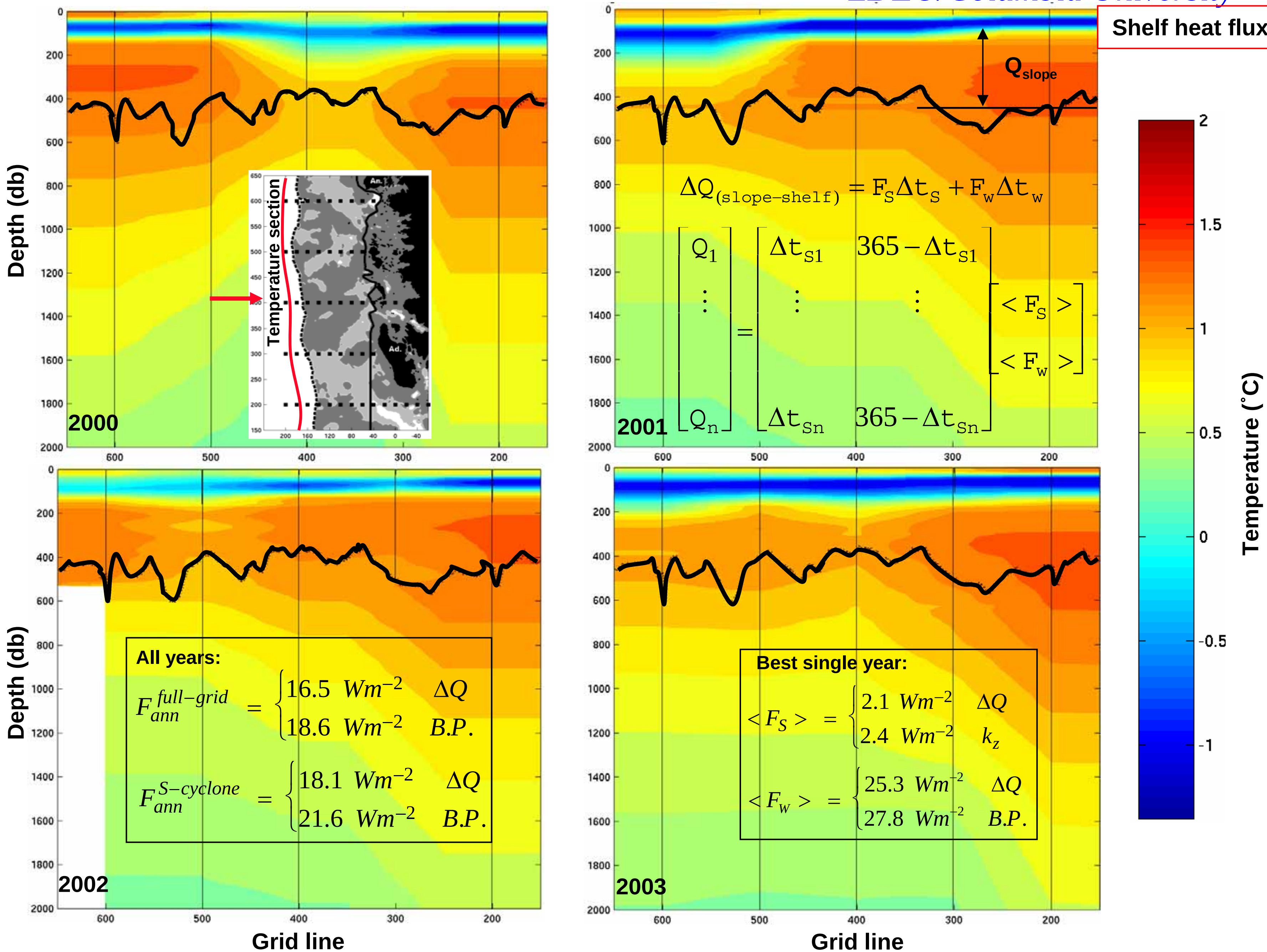
$$SD_W = \left(\frac{1}{\sigma_i}\right)\left[\int_{z_{wm}}^{z_{wc}} (S - S_{wc})\,dz\right] - SD_S$$

F_T: Bulk Parameter vs Measured (AnzFlux, 1994)



$\langle F_T^{BP} \rangle_W$ = 29.67 Wm^2 (*Martinson & Iannuzzi*, 1998)
$\langle F_T^{Obs} \rangle_W$ = 27.7 Wm^2 (*McPhee et al.*, 1999)

Shelf heat flux



$$\Delta Q_{(slope-shelf)} = F_s \Delta t_s + F_w \Delta t_w$$

$$\begin{bmatrix} Q_1 \\ \vdots \\ Q_n \end{bmatrix} = \begin{bmatrix} \Delta t_{s1} & 365-\Delta t_{s1} \\ \vdots & \vdots \\ \Delta t_{sn} & 365-\Delta t_{sn} \end{bmatrix} \begin{bmatrix} \langle F_s \rangle \\ \langle F_w \rangle \end{bmatrix}$$

All years:

$$F_{ann}^{full-grid} = \begin{cases} 16.5\ Wm^{-2} & \Delta Q \\ 18.6\ Wm^{-2} & B.P. \end{cases}$$

$$F_{ann}^{S-cyclone} = \begin{cases} 18.1\ Wm^{-2} & \Delta Q \\ 21.6\ Wm^{-2} & B.P. \end{cases}$$

Best single year:

$$\langle F_S \rangle = \begin{cases} 2.1\ Wm^{-2} & \Delta Q \\ 2.4\ Wm^{-2} & k_z \end{cases}$$

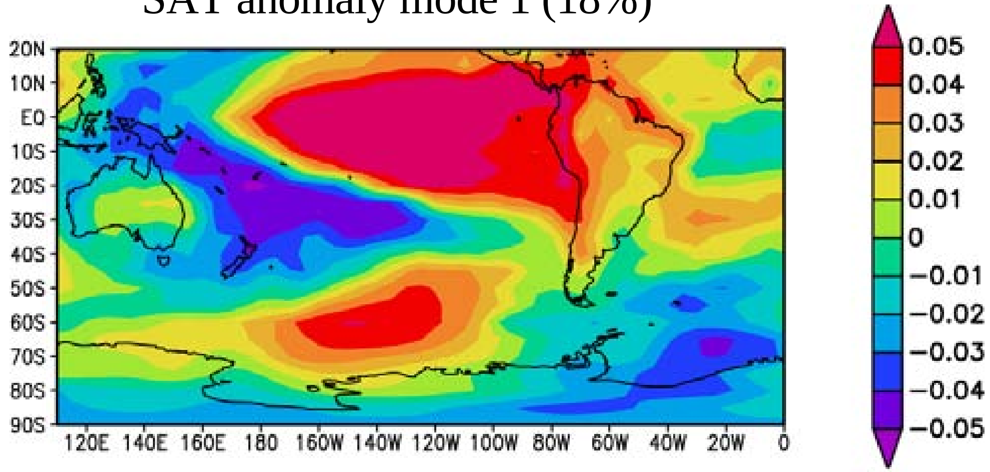
$$\langle F_W \rangle = \begin{cases} 25.3\ Wm^{-2} & \Delta Q \\ 27.8\ Wm^{-2} & B.P. \end{cases}$$

Support slides

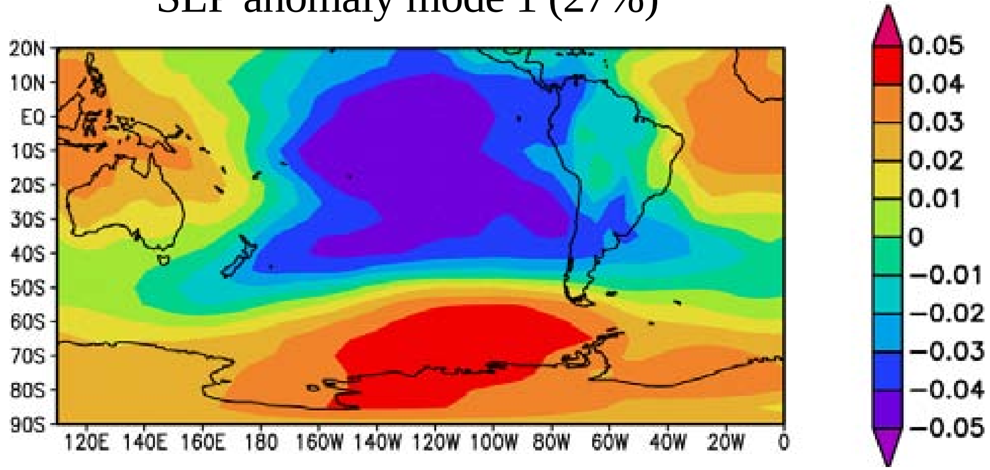
Global Forcing

ENSO impact is manifested predominantly as Antarctic Dipole (ADP)

SAT anomaly mode 1 (18%)



SLP anomaly mode 1 (27%)



Yuan and Martinson, GRL, 2001

Optimal Multi-Parameter (OMP) Analysis

Optimize:

$\mathbf{wAx} = \mathbf{wb}$

Constrained by:

$\mathbf{Ix} \geq \mathbf{0}$

Solution:

$\mathbf{x} = \mathbf{Cb}$

Uncertainty:

$\mathrm{Var}[\mathbf{x}] = \mathbf{C}\Sigma_{\mathbf{b}}\mathbf{C}^{\mathbf{T}}$

$\mathbf{C} = [\mathbf{A}^T\mathbf{w}^T\mathbf{w}\mathbf{A}]^{-1}\mathbf{A}^T\mathbf{w}^T\mathbf{w}$
= pseudo-inverse

$\Sigma_{\mathbf{b}}$ = autocovariance matrix across grid
= $m^{-1}\mathbf{D}\mathbf{D}^{\mathbf{T}}$

D = data matrix of all **b** column vectors across grid

Property Matrix (A) | **x** | **b**

WW properties, UCDW properties, DW properties

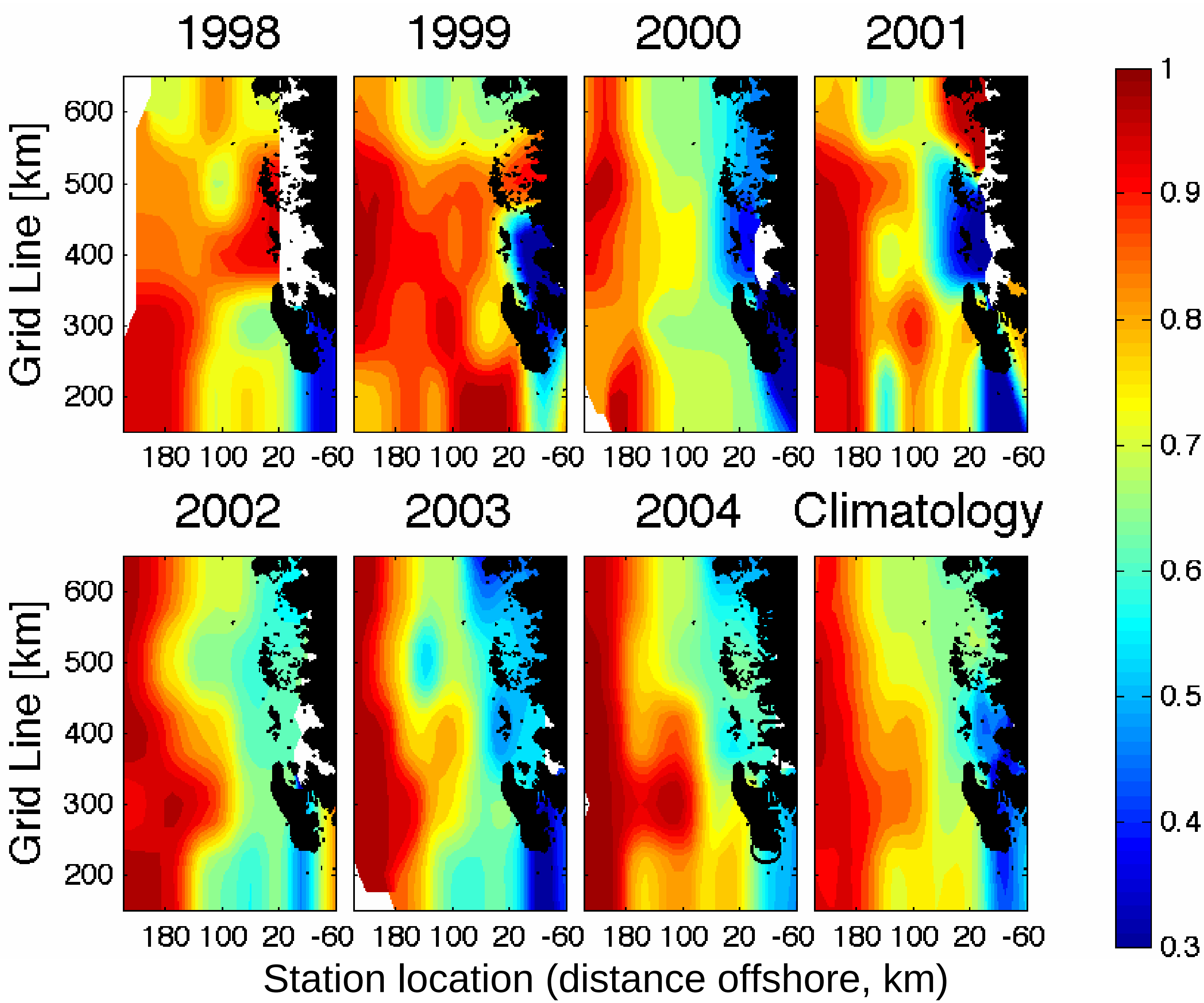
$$\begin{bmatrix} S_{ww} & S_{ucdw} & S_{dw} \\ N^*_{ww} & N^*_{ucdw} & N^*_{dw} \\ Si^*_{ww} & Si^*_{ucdw} & Si^*_{dw} \\ 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} x_{ww} \\ x_{ucdw} \\ x_{dw} \end{bmatrix} = \begin{bmatrix} S_{obs} \\ N^*_{obs} \\ Si^*_{obs} \\ 1 \end{bmatrix}$$

$N^* = [NO] - 16PO_4$ — *Gruber and Sarmiento*, 1997
$Si^* = [Si(OH)4] - [NO]$ — *Sarmiento et al.*, 2004

$$\mathbf{w} = \begin{bmatrix} 1/\hat{\sigma}_S & & & \\ & 1/\hat{\sigma}_{N*} & & \\ & & 1/\hat{\sigma}_{Si*} & \\ & & & \infty \end{bmatrix}$$

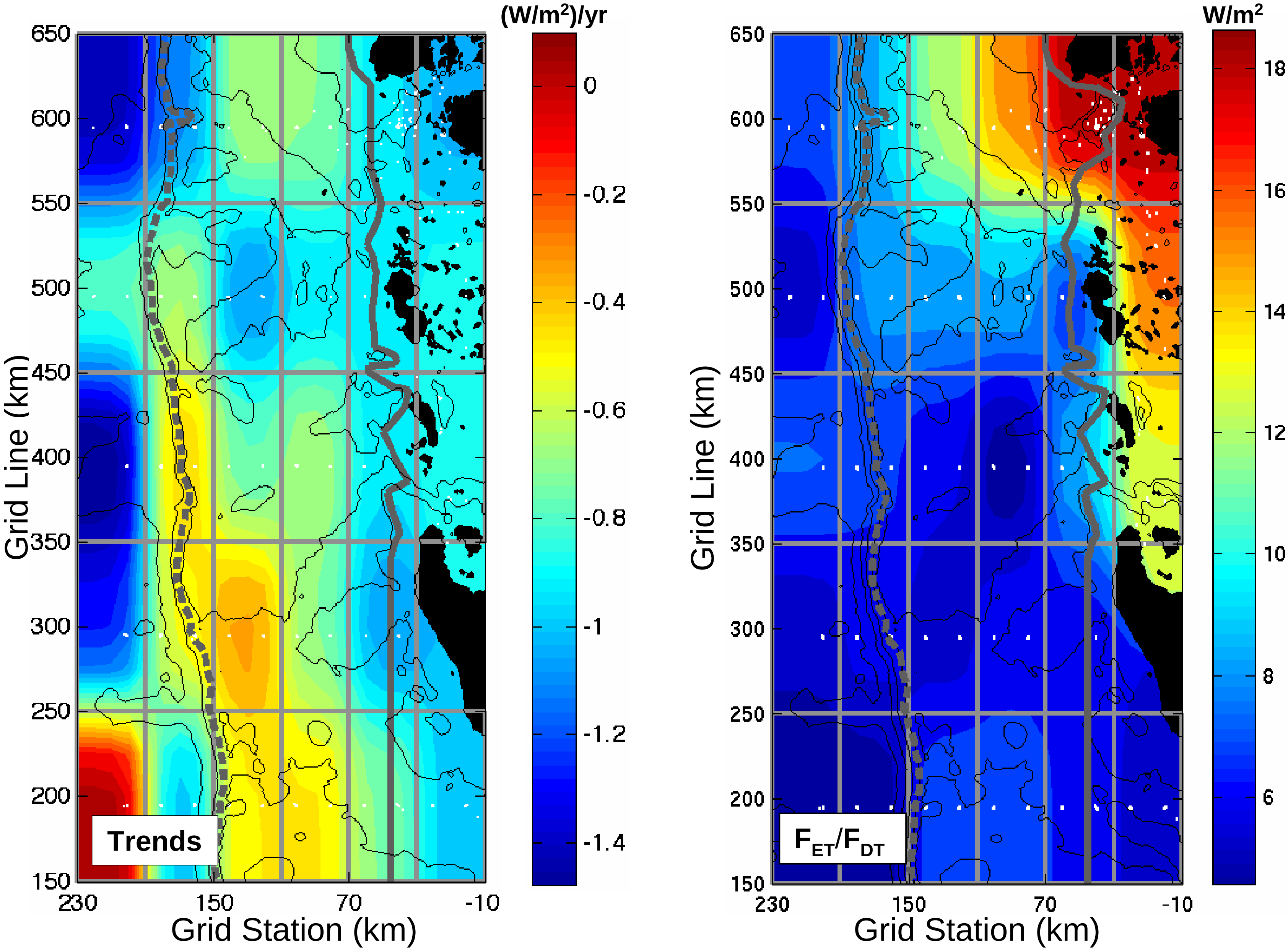
Pathways of heat

Fraction Pure UCDW



Trends in heat flux and flux component ratios

Heat flux



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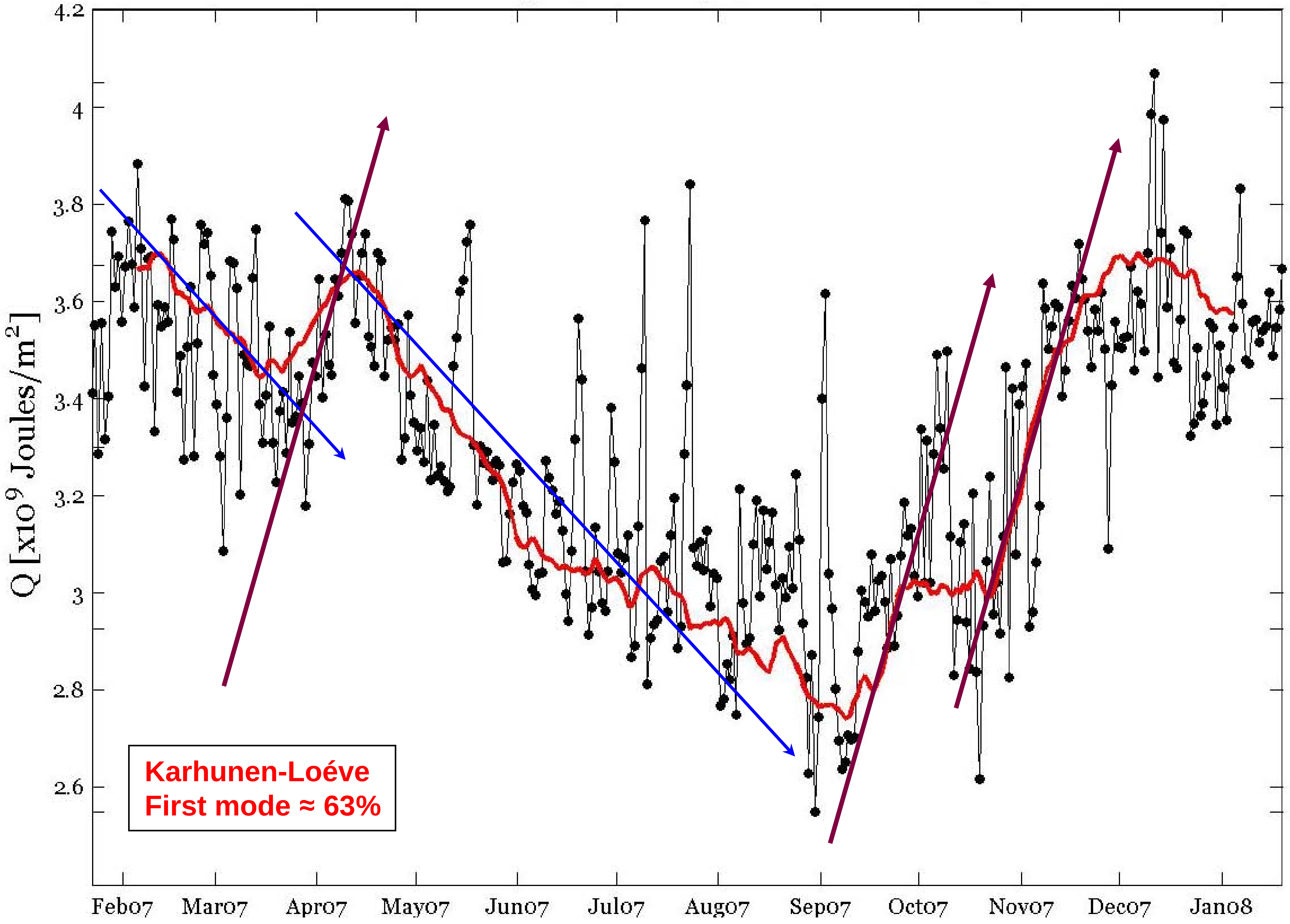
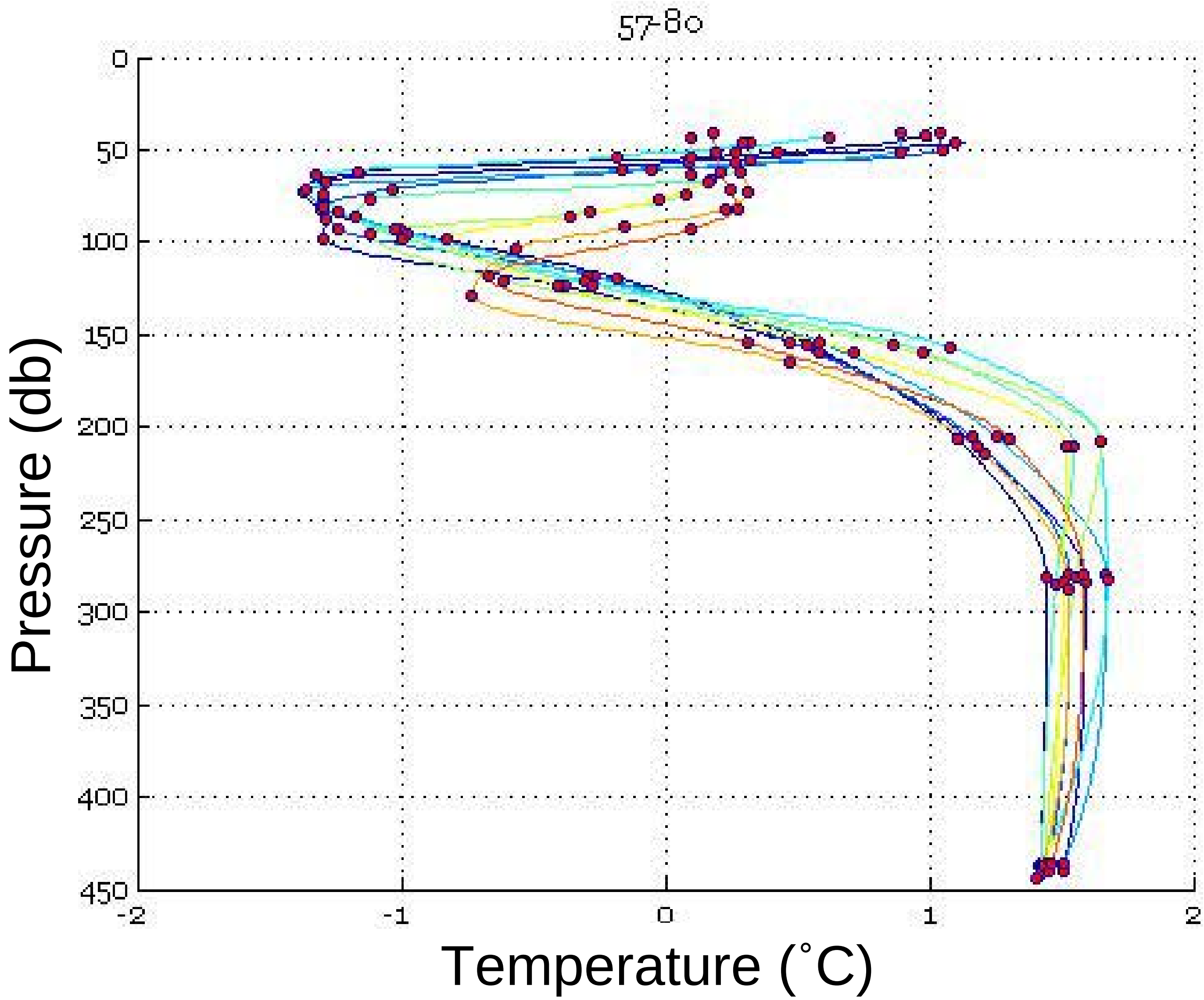
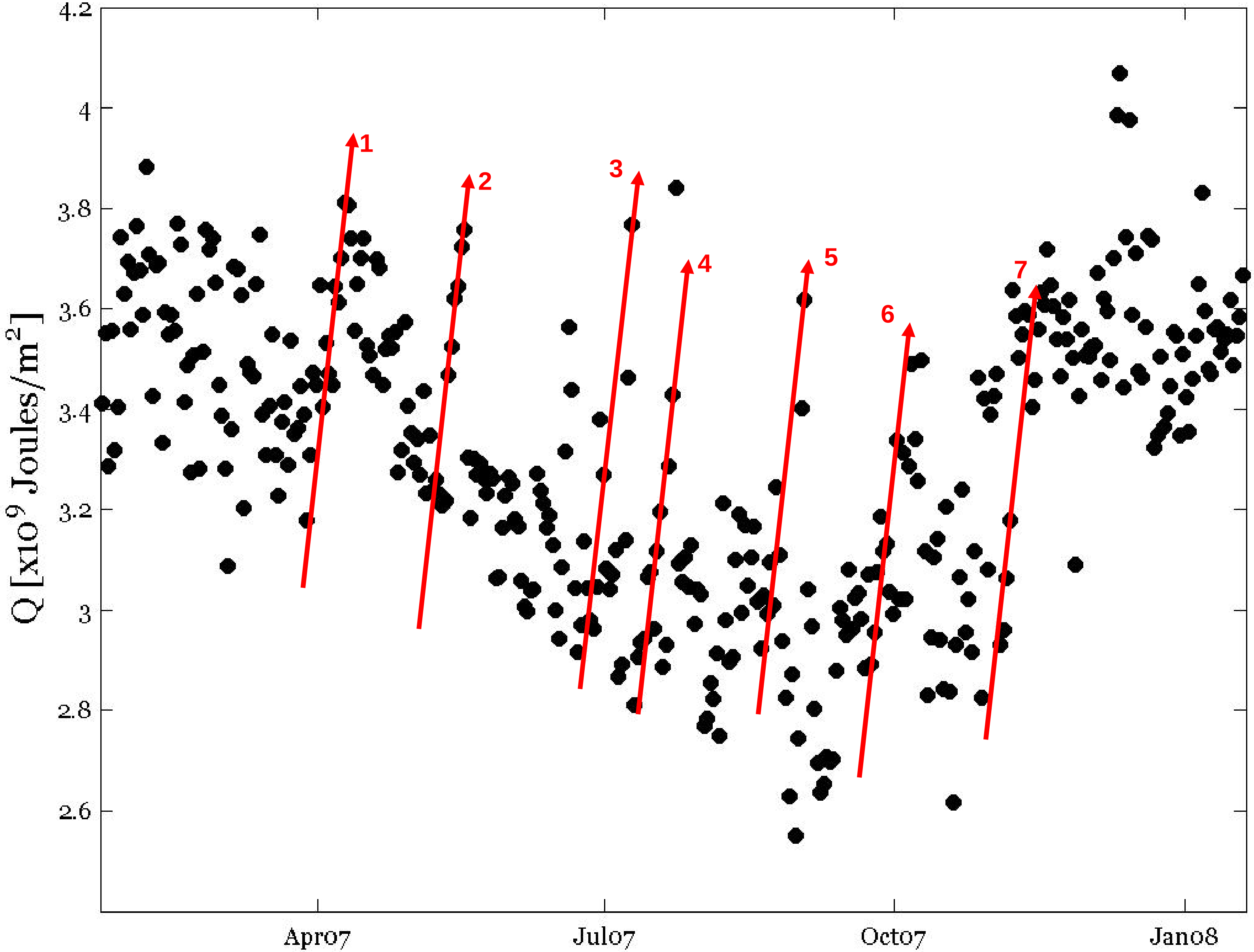


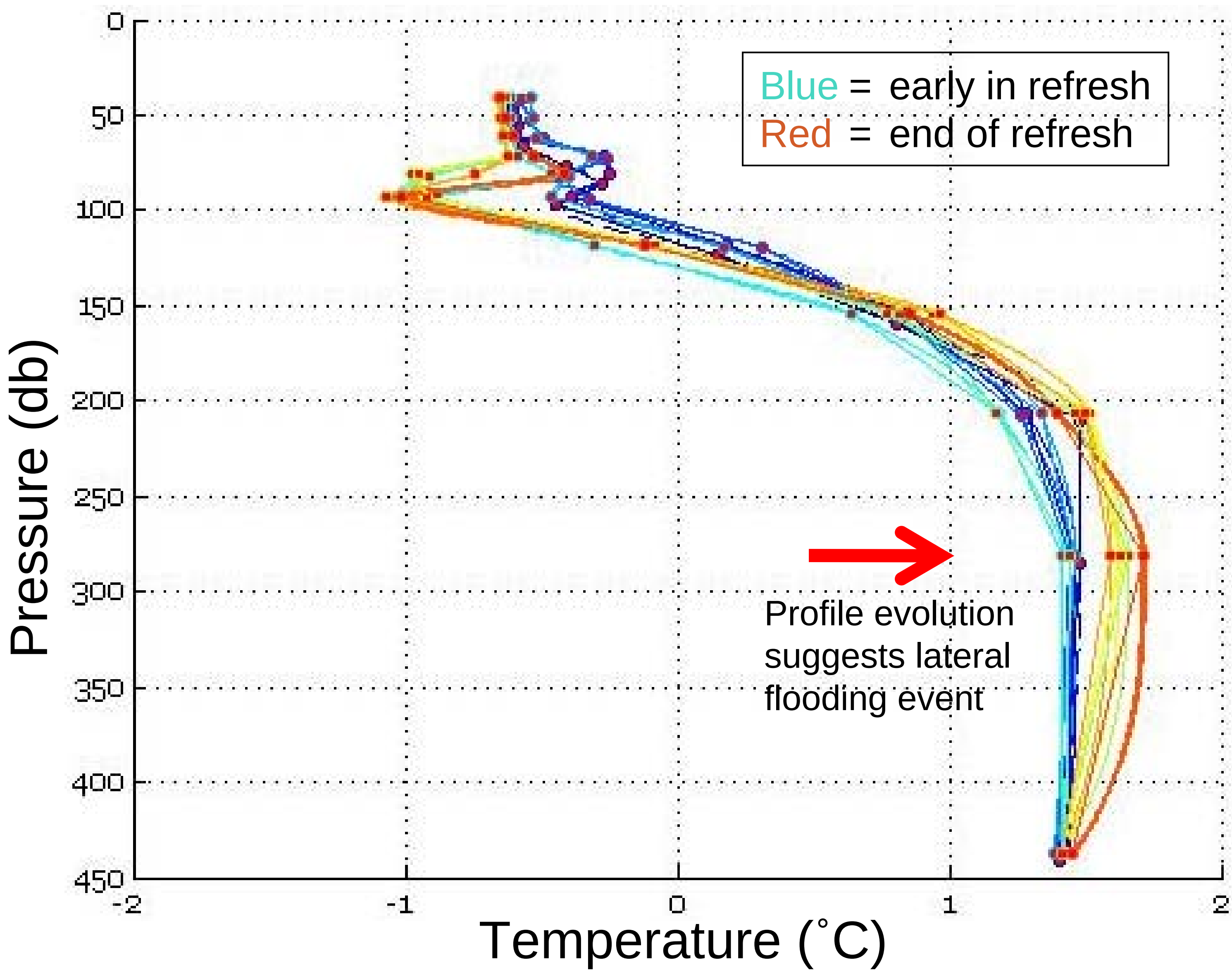
Signal recharge 1



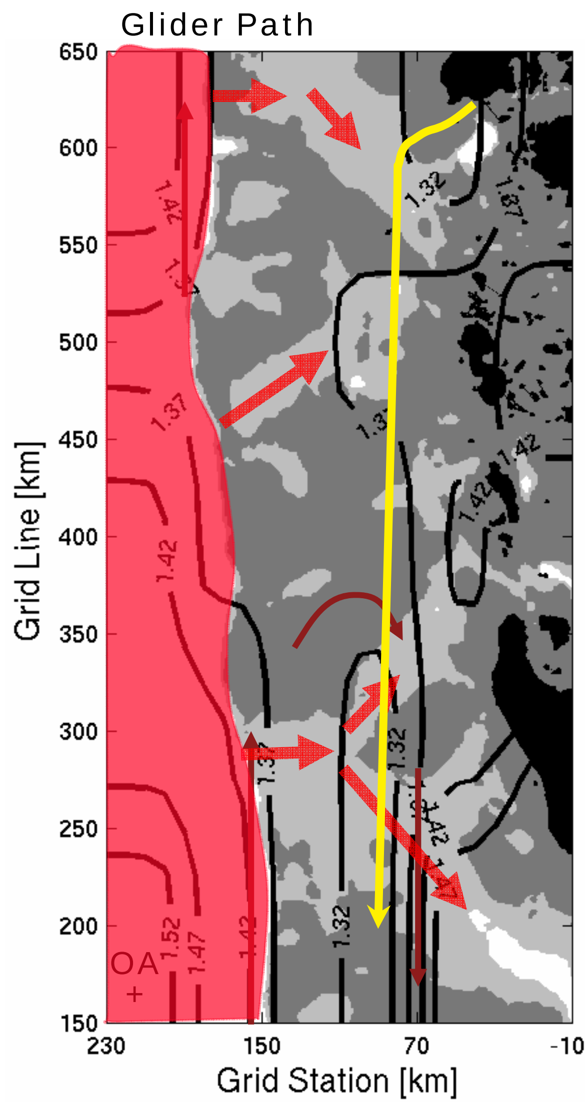
Finding flooding events in the noise



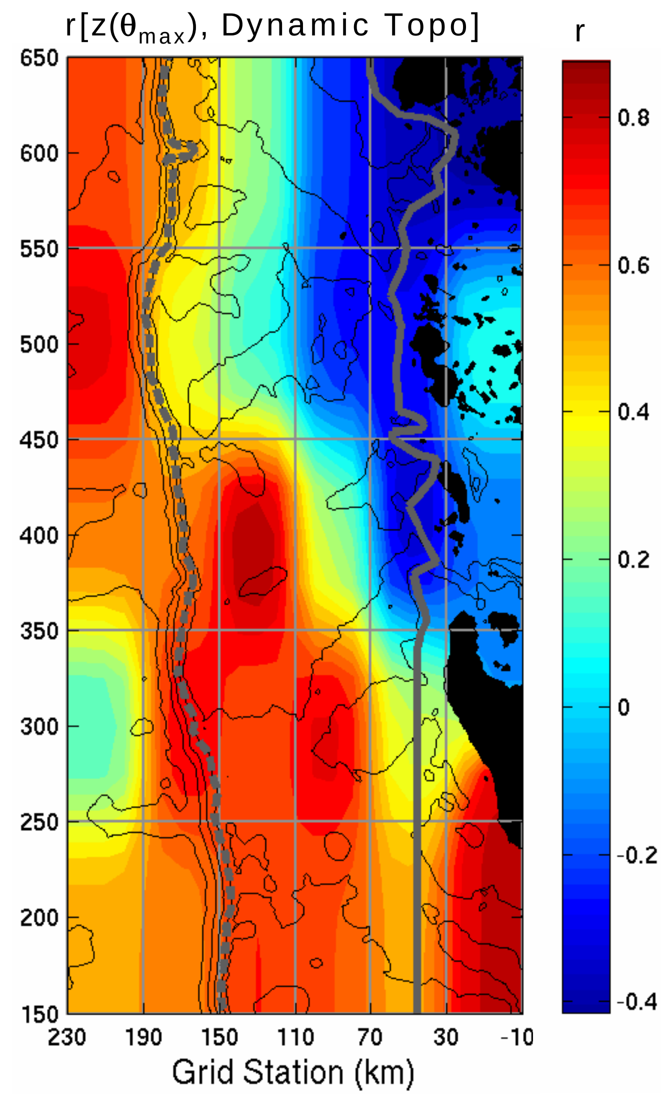
Event 2


Blue = early in refresh
Red = end of refresh
Profile evolution suggests lateral flooding event
Pressure (db)
Temperature (˚C)
0
50
100
150
200
250
300
350
400
450
-2
-1
0
1
2

Pathways of heat



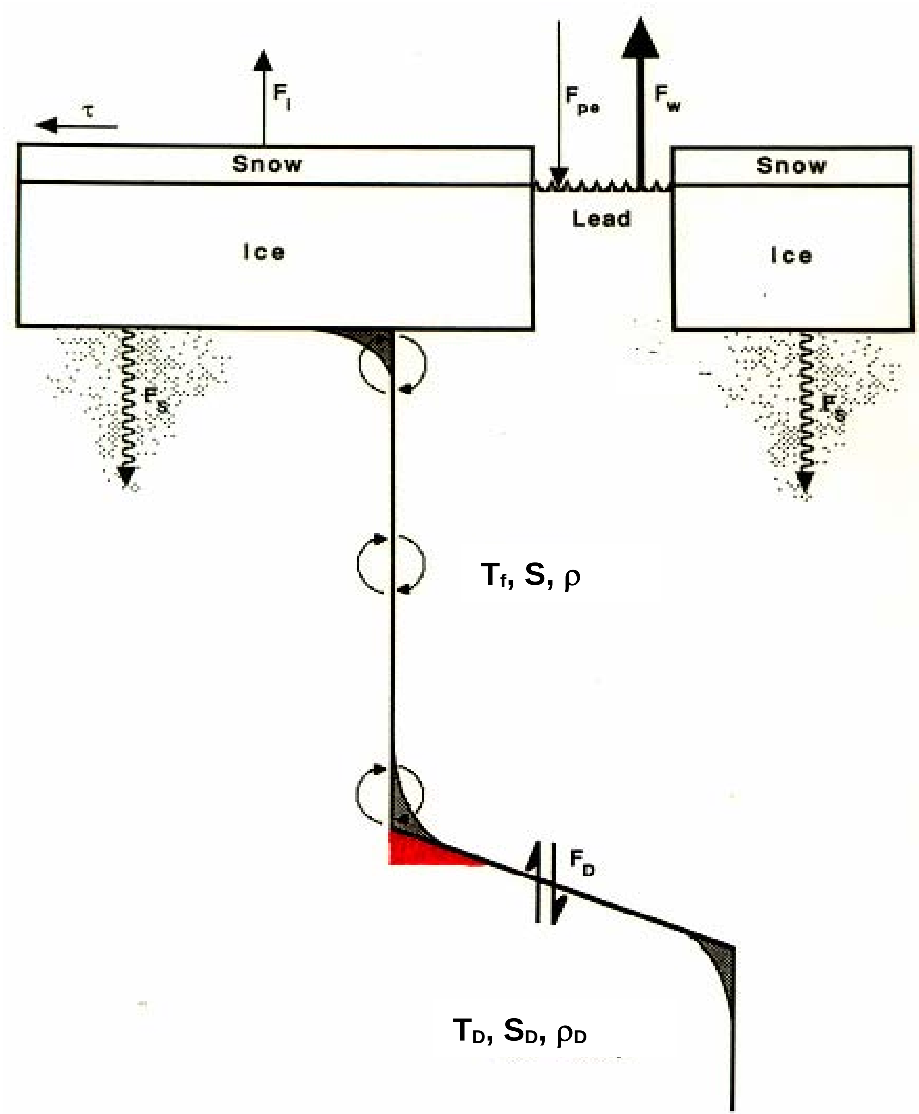
Individual years consistent with drifter data



UCDW pulled onto shelf by upwelling dynamics (likely wind-driven)

Shelf heat flux

Ocean-Ice Interaction



Martinson, JGR, 1990