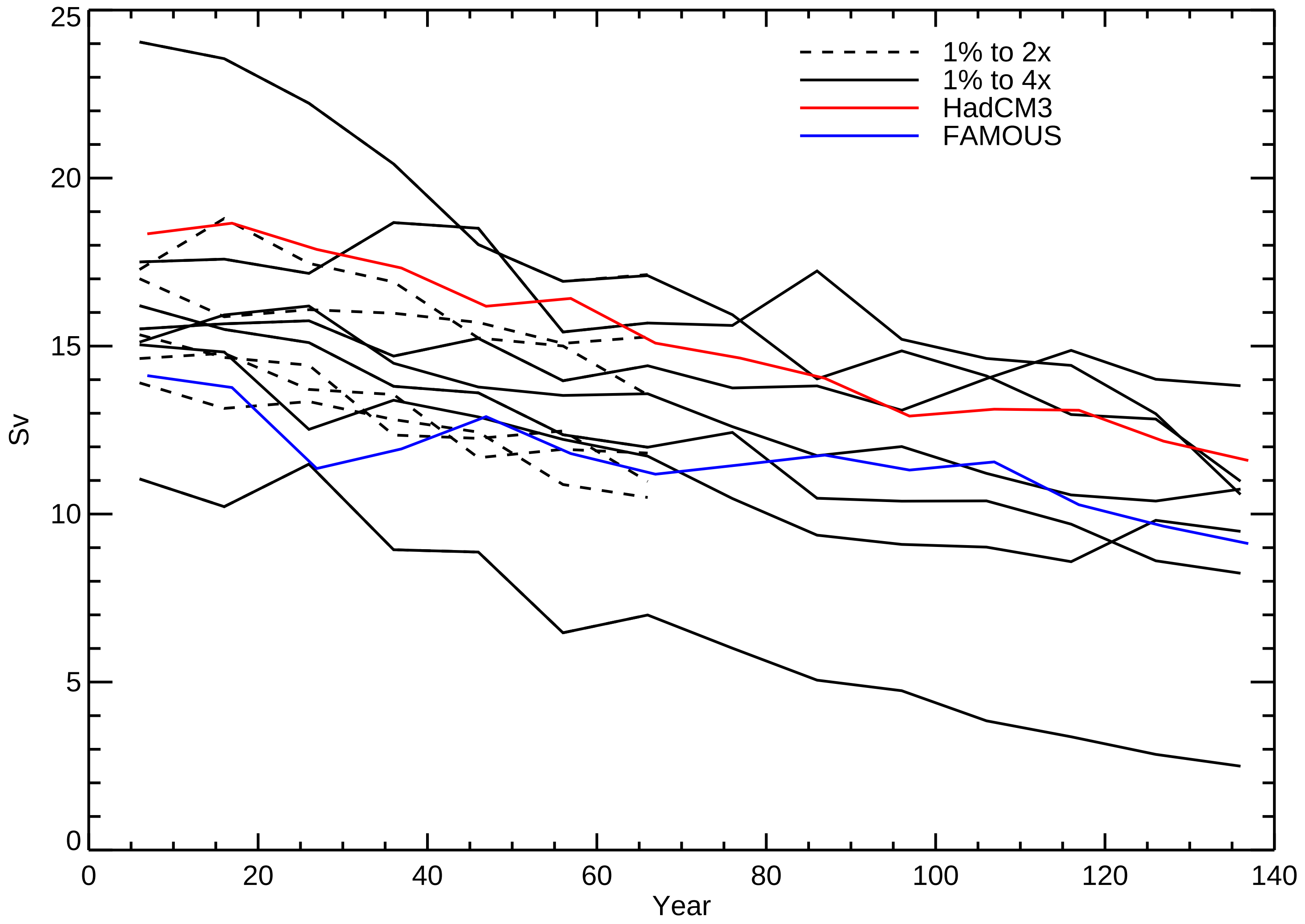
Energetic analysis of changes in the AMOC under increasing CO_2

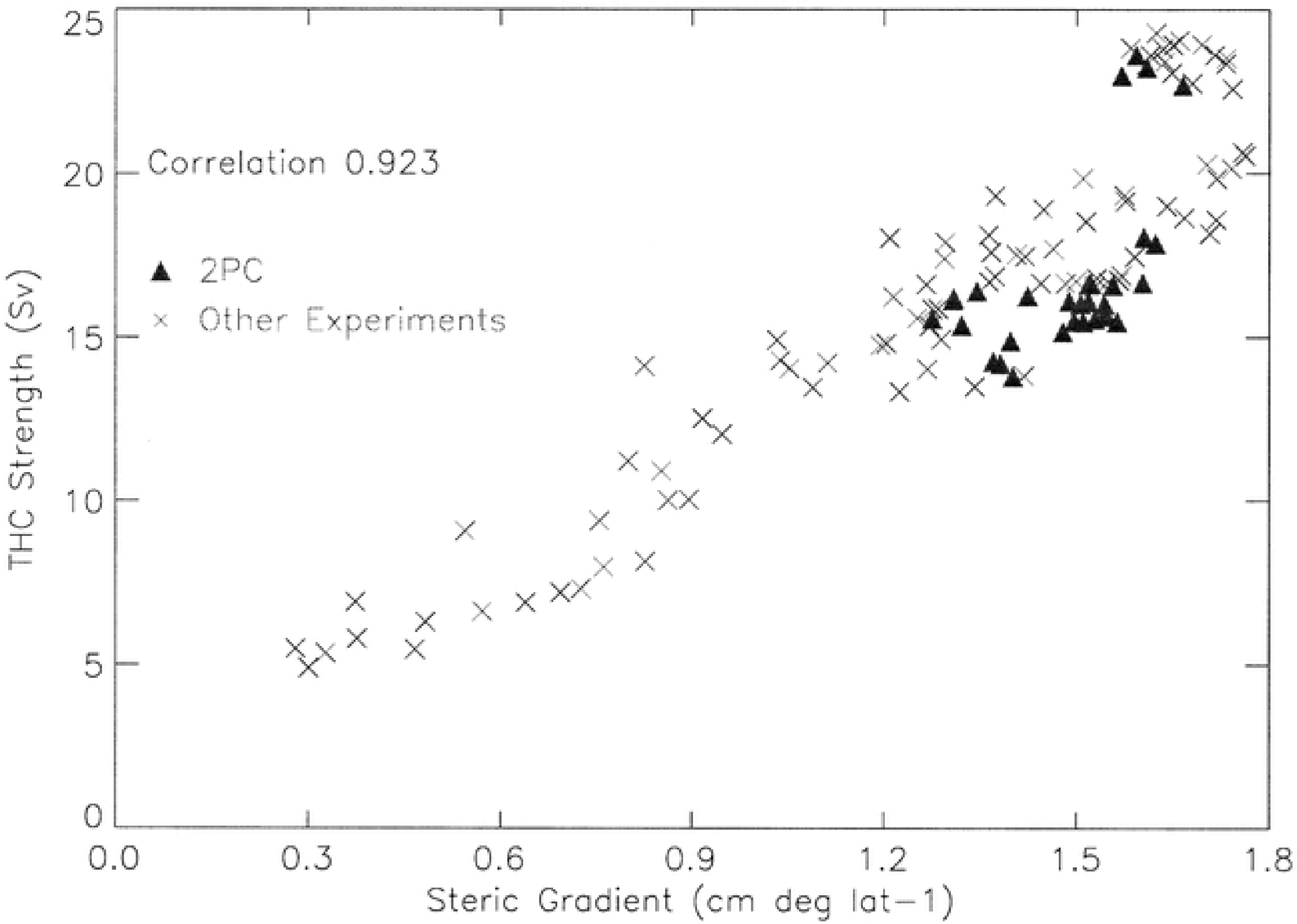
Jonathan Gregory[1,3] and Rémi Tailleux[2]
NCAS-Climate[1], Department of Meteorology[2],
University of Reading
and Met Office Hadley Centre[3], Exeter

Maximum AMOC streamfunction in IPCC AR4 CO_2 experiments



We want a physical understanding of the different responses

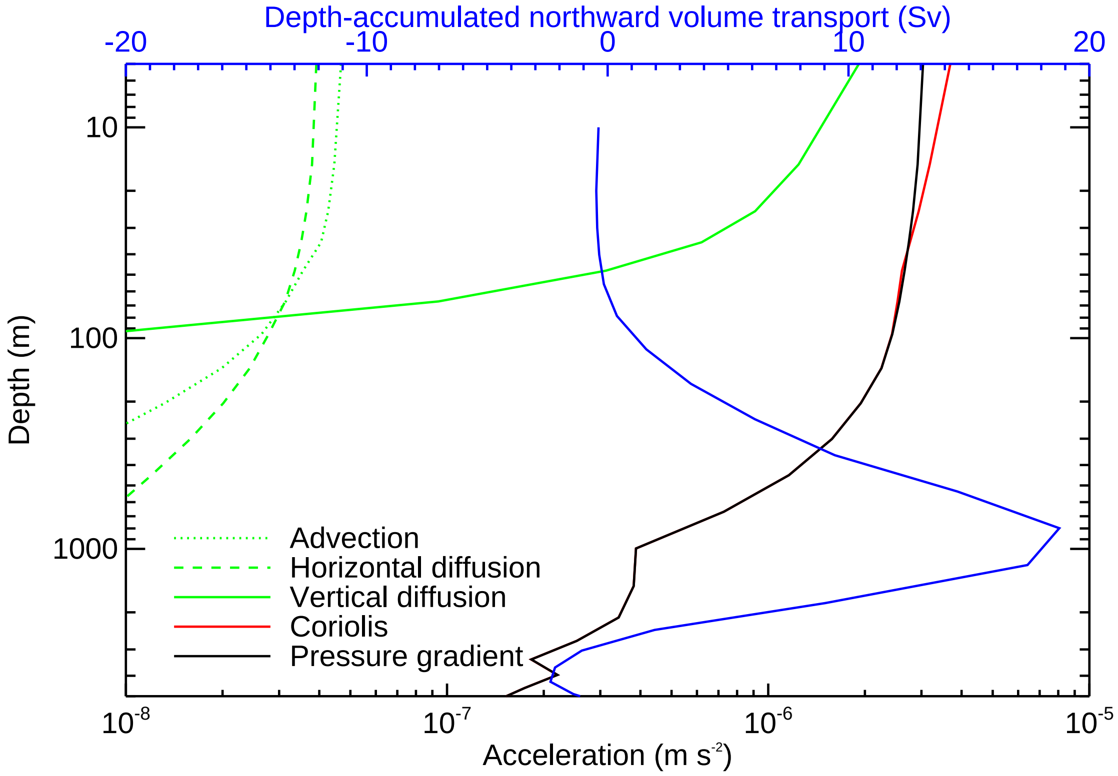
Relationship between meridional density gradient and AMOC



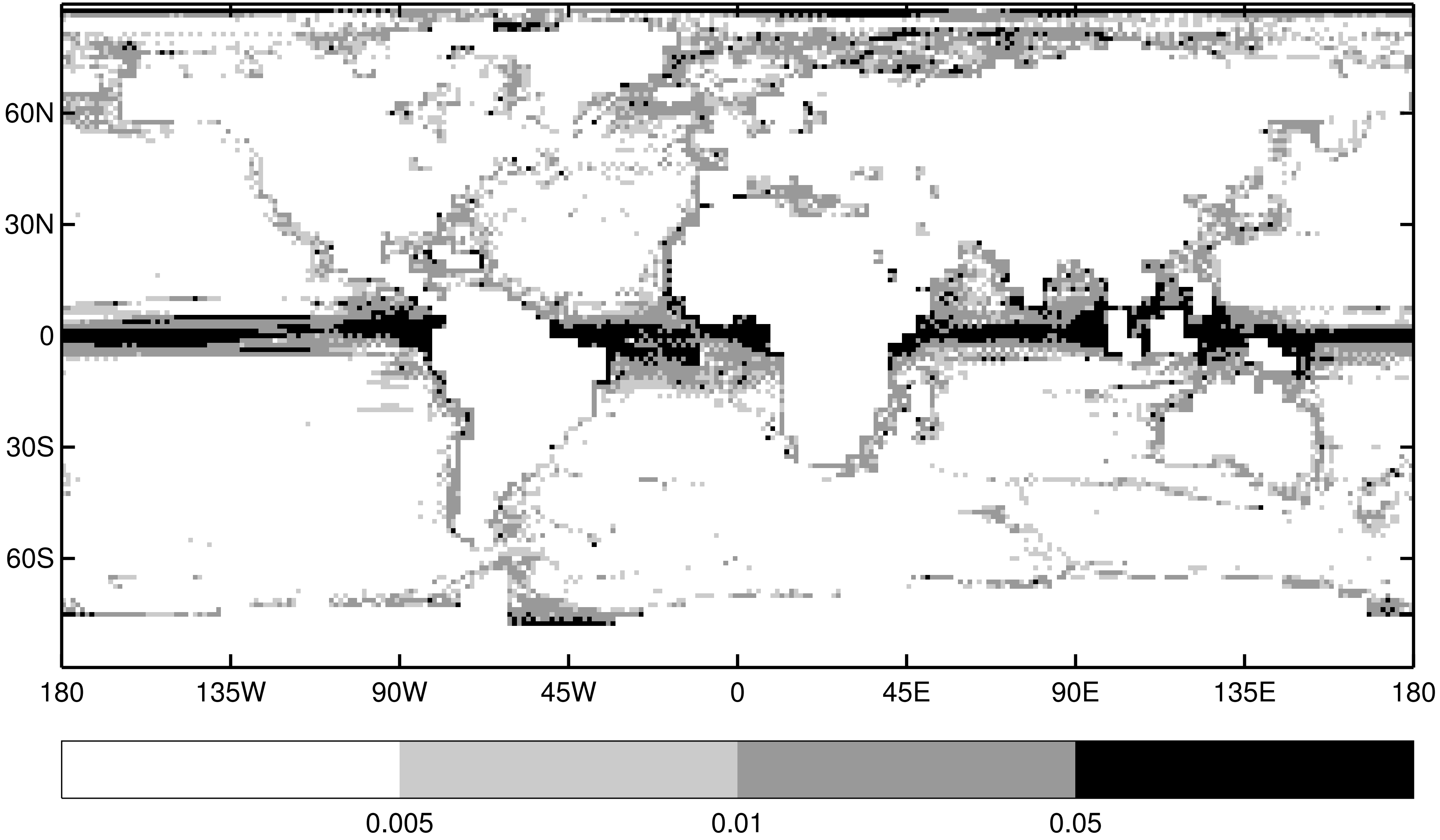
HadCM3 with CO_2 increasing at 2% yr^{-1}, Thorpe *et al.* (2001)

Force balance of the (HadCM3) ocean circulation

$$\frac{\mathrm{D}\mathbf{u}_h}{\mathrm{D}t} = \frac{\partial \mathbf{u}_h}{\partial t} \underbrace{+(\mathbf{u}\cdot\boldsymbol{\nabla})\mathbf{u}_h}_{\text{advection}} = \underbrace{-\frac{1}{\rho_0}\boldsymbol{\nabla}_h p}_{\text{pressure gradient}} \underbrace{-\mathbf{f}\times\mathbf{u}_h}_{\text{Coriolis}} \underbrace{+\frac{1}{\rho_0}\mathbf{F}_v}_{\text{vertical mixing}} \underbrace{+\frac{1}{\rho_0}\mathbf{F}_h}_{\text{horizontal mixing}}$$



Below the Ekman layer, the circulation is almost completely geostrophic, including the AMOC



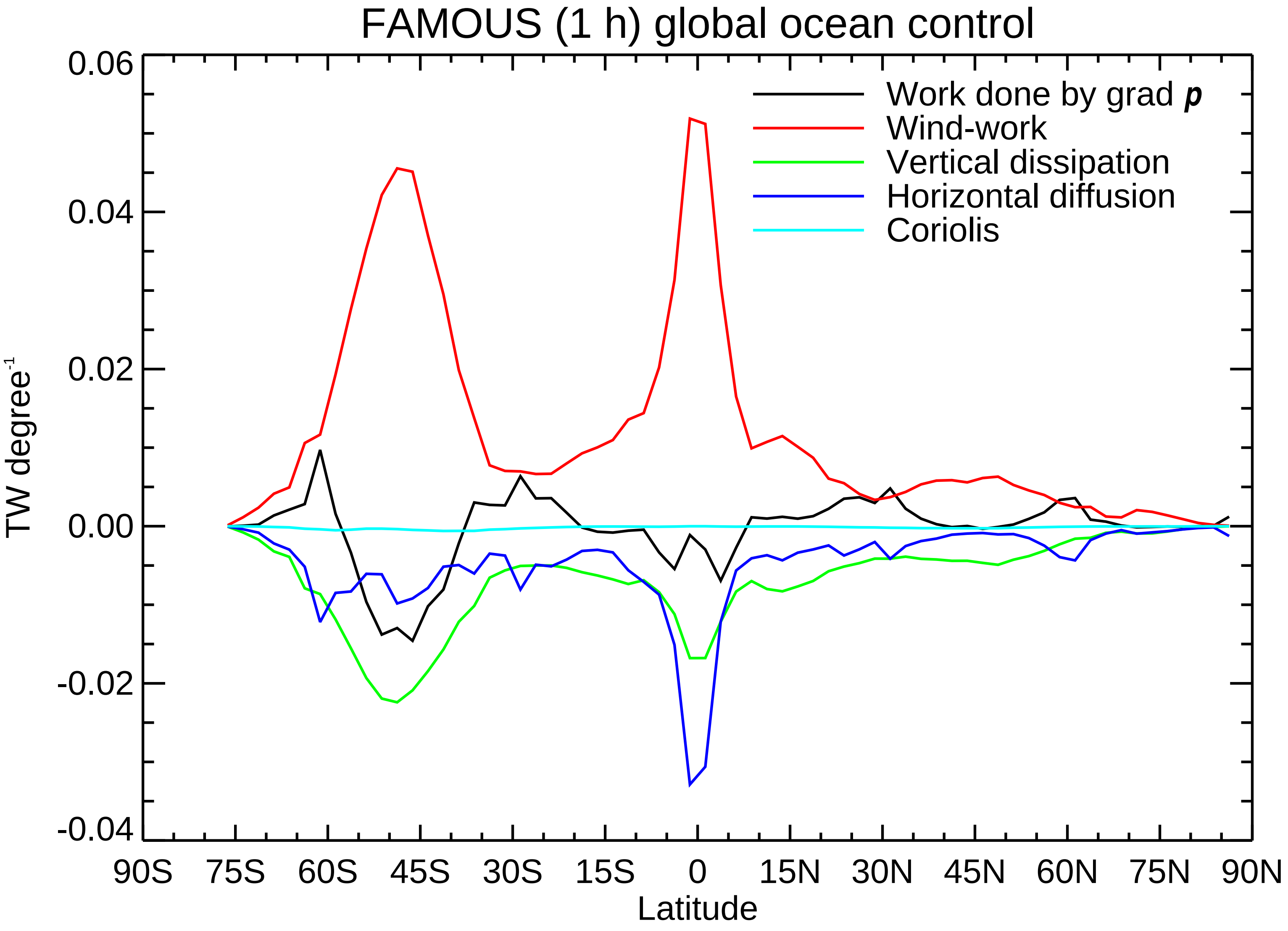
Ratio of net ageostrophic force to $\nabla_h p$ 55–800 m in HadCM3

Kinetic energy balance of the ocean circulation

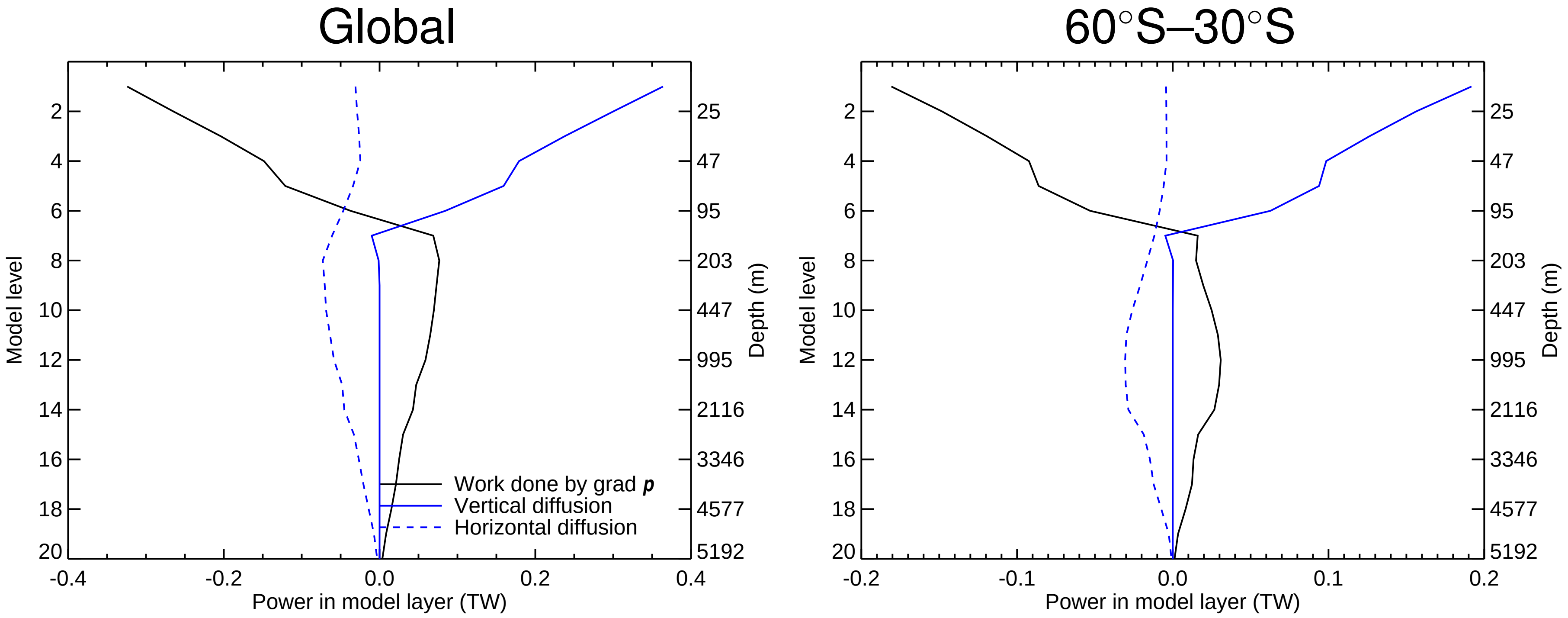
$$\frac{\partial}{\partial t}\frac{u_h^2}{2} = -\mathbf{u}_h \cdot ((\mathbf{u}\cdot\boldsymbol{\nabla})\mathbf{u}_h) \; -\frac{1}{\rho_0}\mathbf{u}_h \cdot \boldsymbol{\nabla}_h p \; -\mathbf{u}_h \cdot \mathbf{f} \times \mathbf{u}_h \; +\frac{1}{\rho_0}\mathbf{u}_h \cdot \mathbf{F}_v \; +\frac{1}{\rho_0}\mathbf{u}_h \cdot \mathbf{F}_h$$

advection	pressure gradient	Coriolis	vertical mixing	horizontal mixing

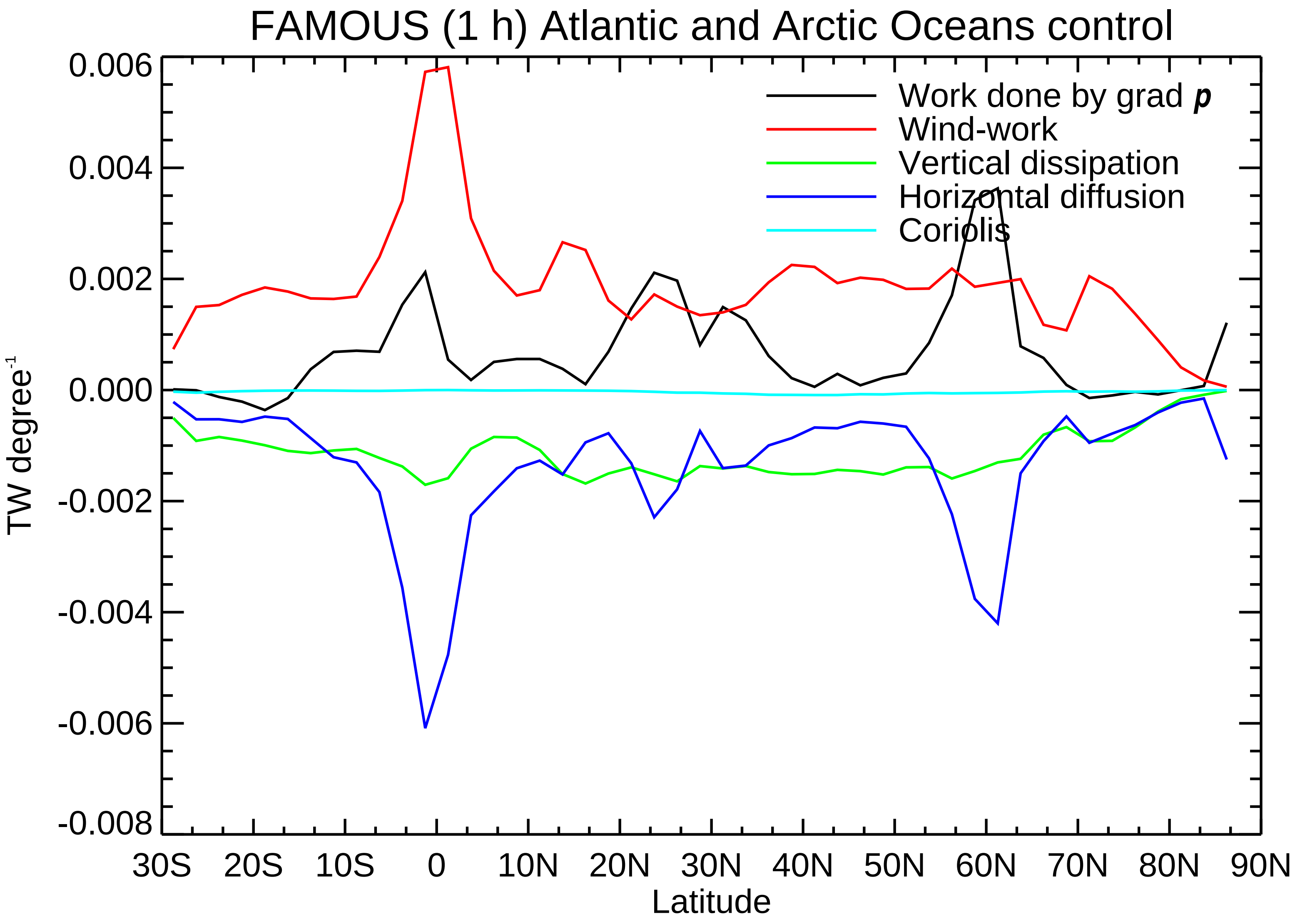
Global ocean kinetic energy balance



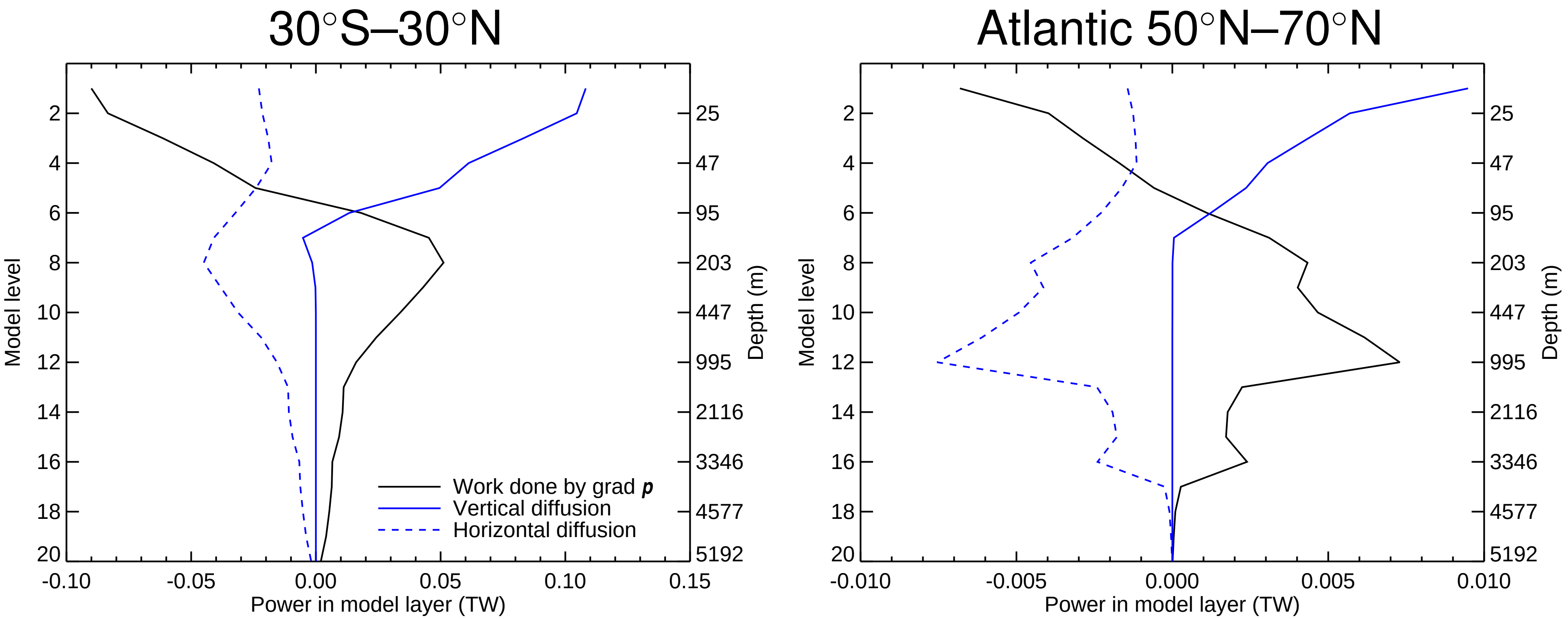
Area-integral of terms in the kinetic energy balance



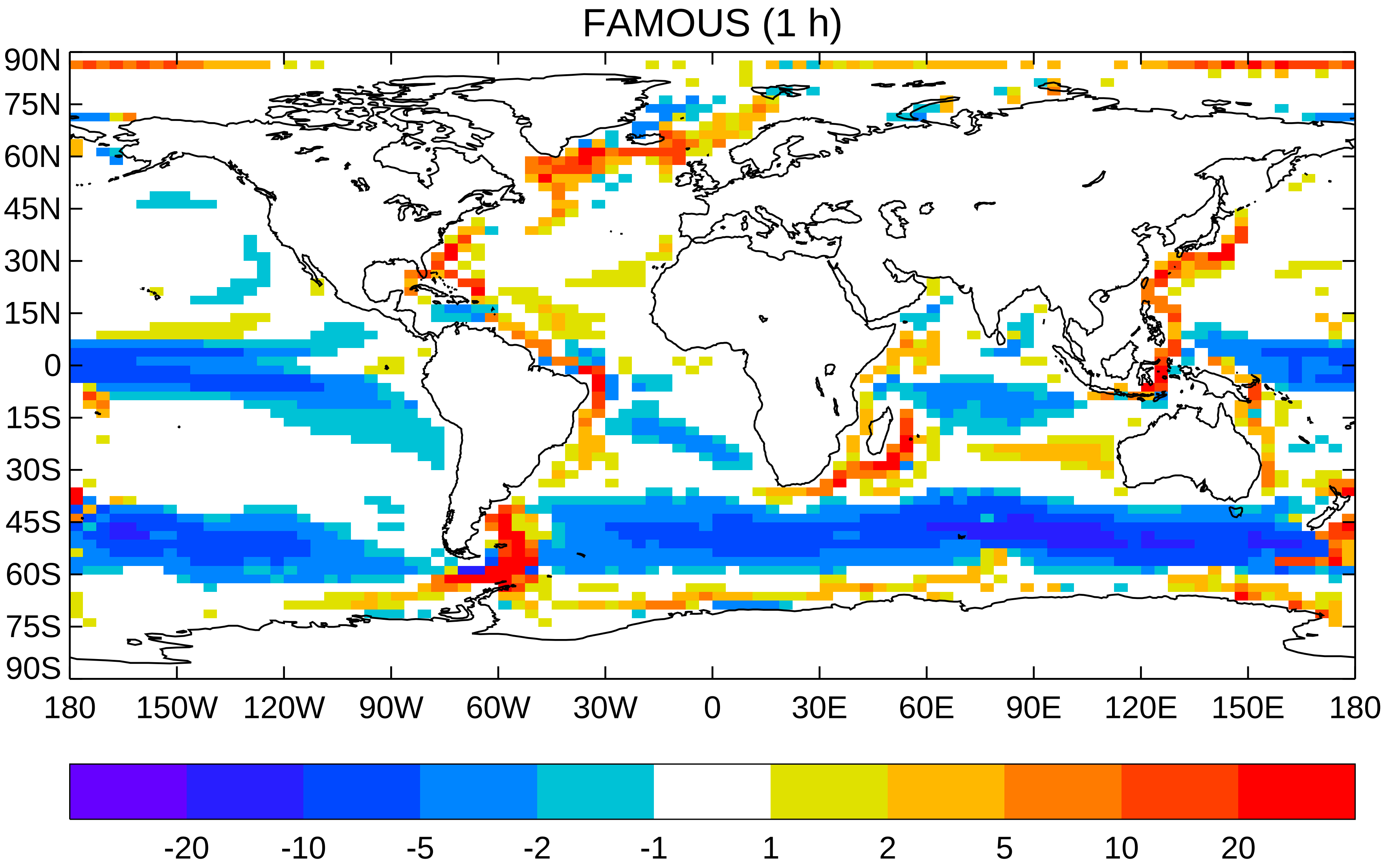
Atlantic Ocean kinetic energy balance



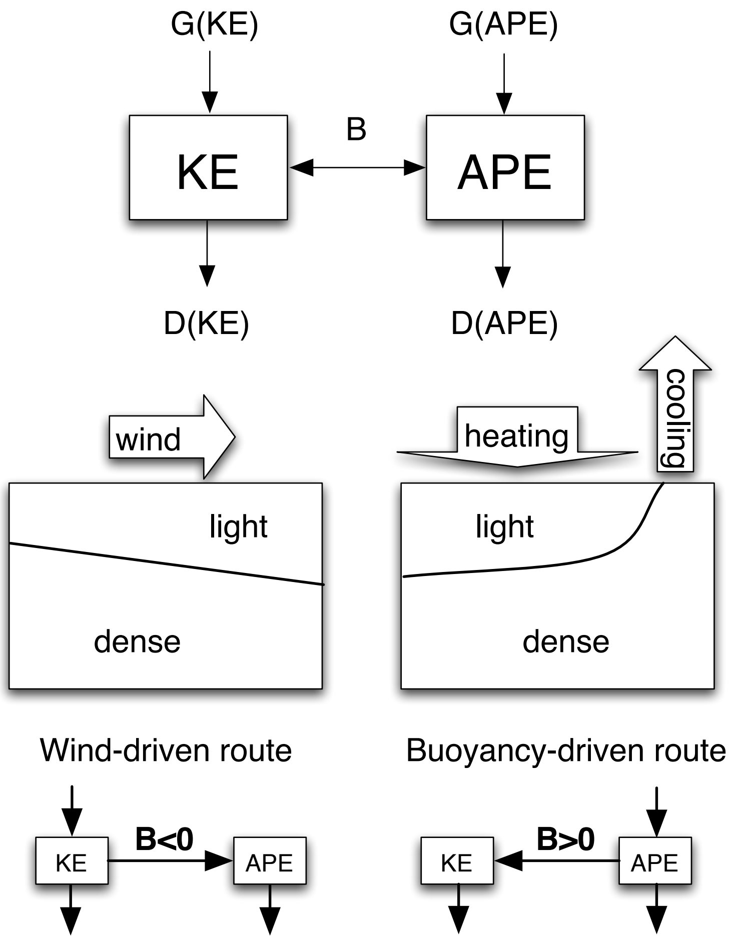
Area-integral of terms in the kinetic energy balance



Work done by the pressure-gradient force $-\mathbf{u}_h \cdot \nabla_h p$



Routes for energy conversion



G(KE)

G(APE)

KE

B

APE

D(KE)

D(APE)

wind

light

dense

heating

cooling

light

dense

Wind-driven route

Buoyancy-driven route

KE

B<0

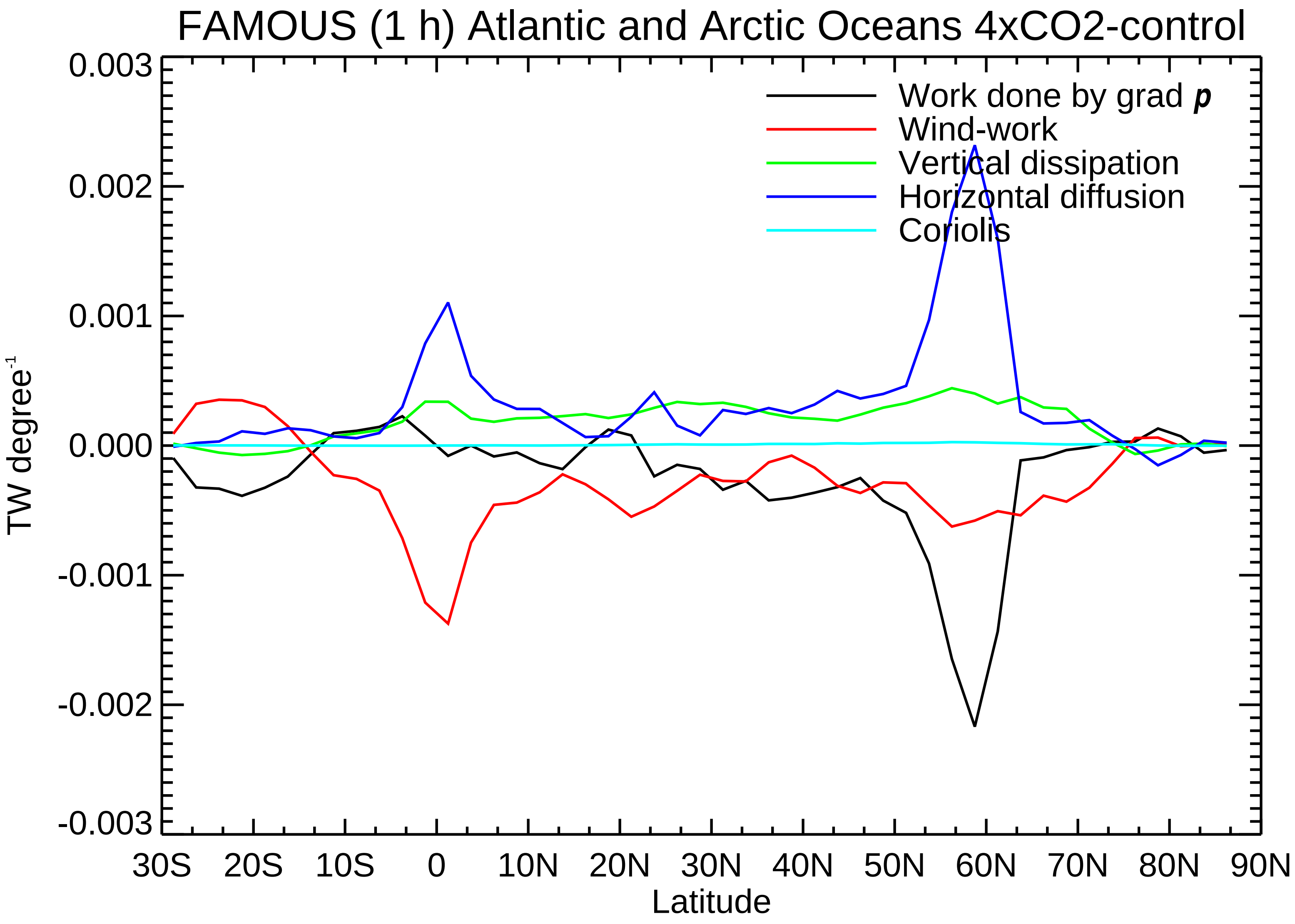
APE

KE

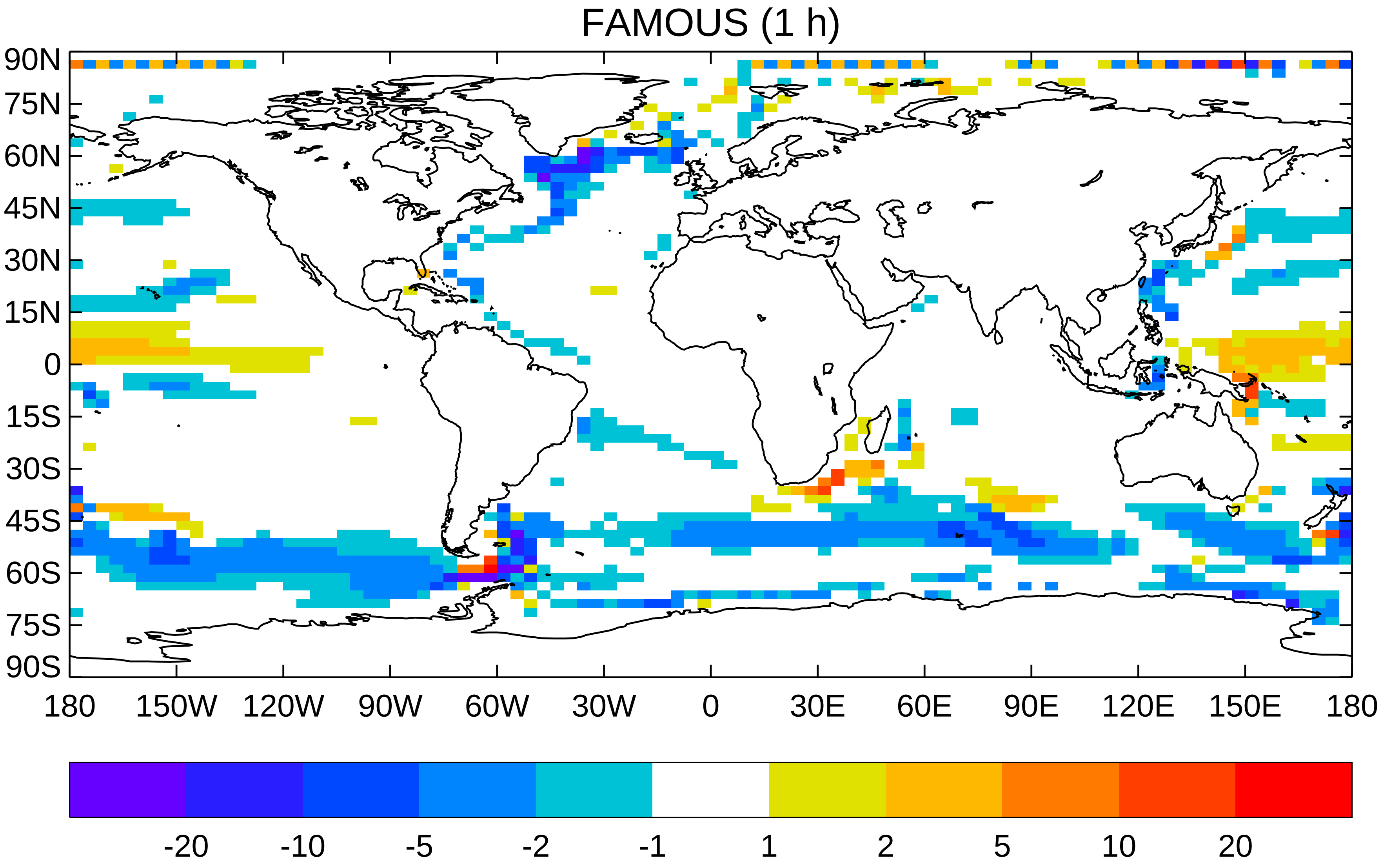
B>0

APE

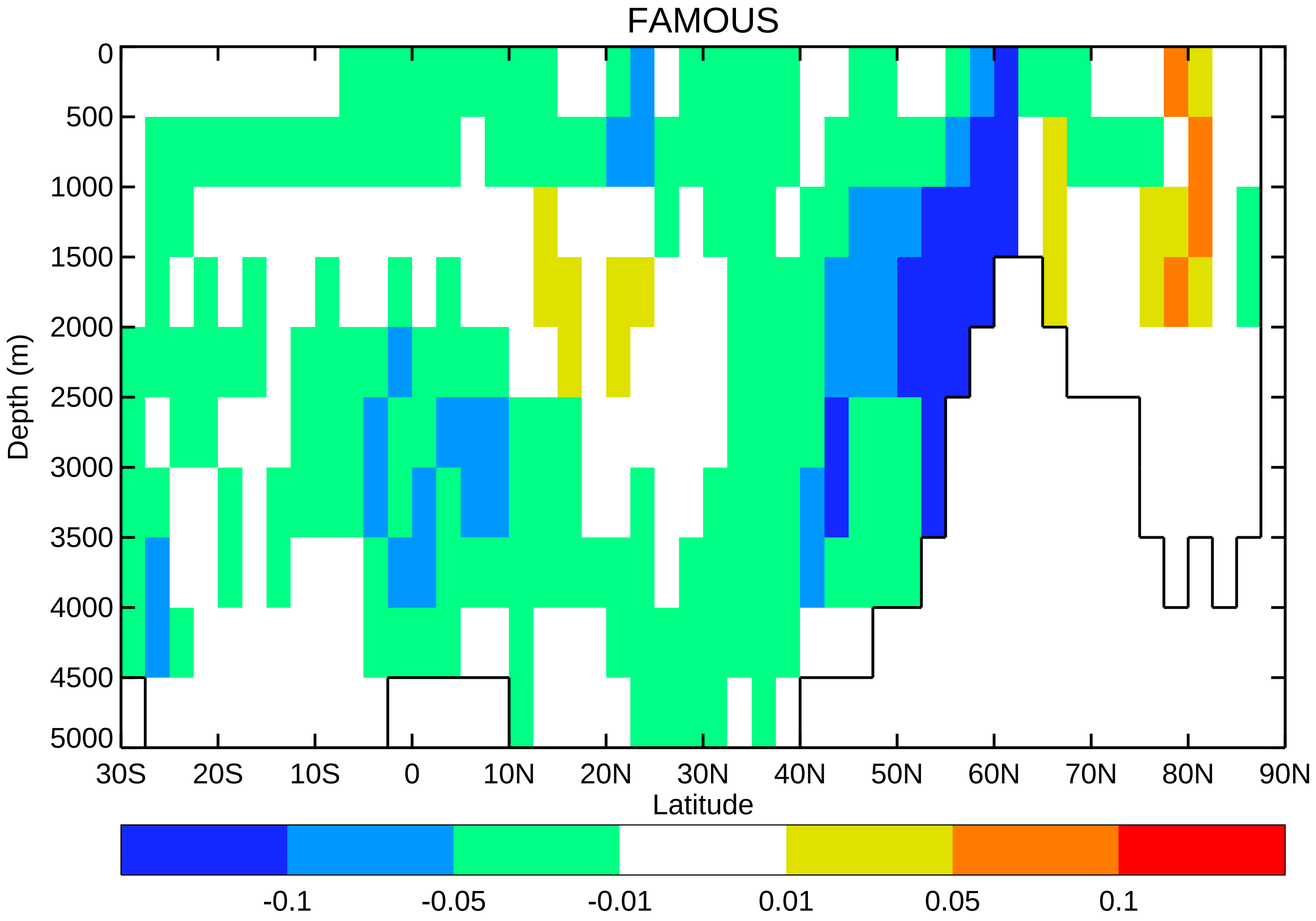
Change in the kinetic energy balance of the Atlantic at 4 × CO_2



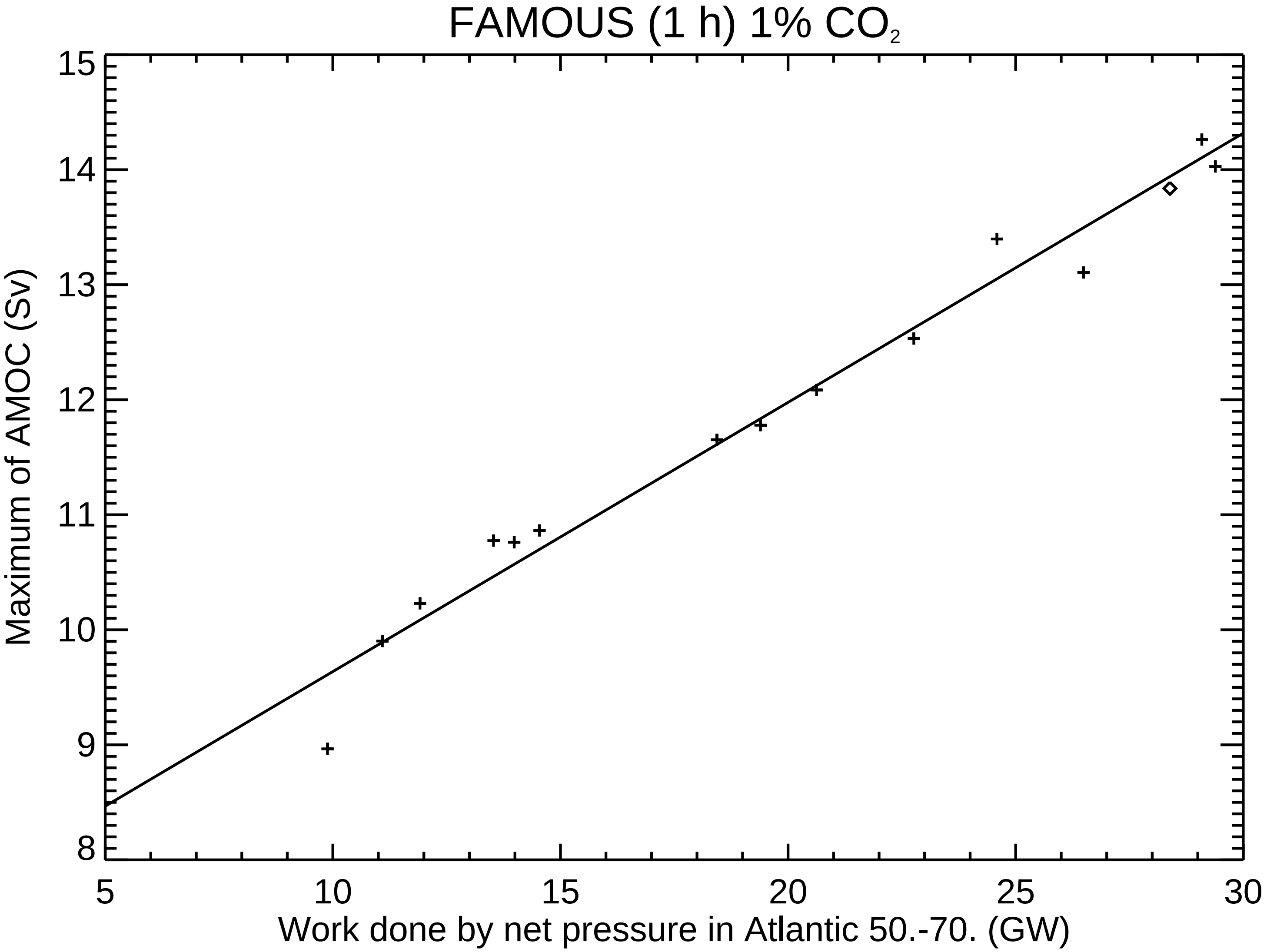
Change in $-\mathbf{u}_h \cdot \boldsymbol{\nabla}_h p$ at $4 \times \mathrm{CO}_2$

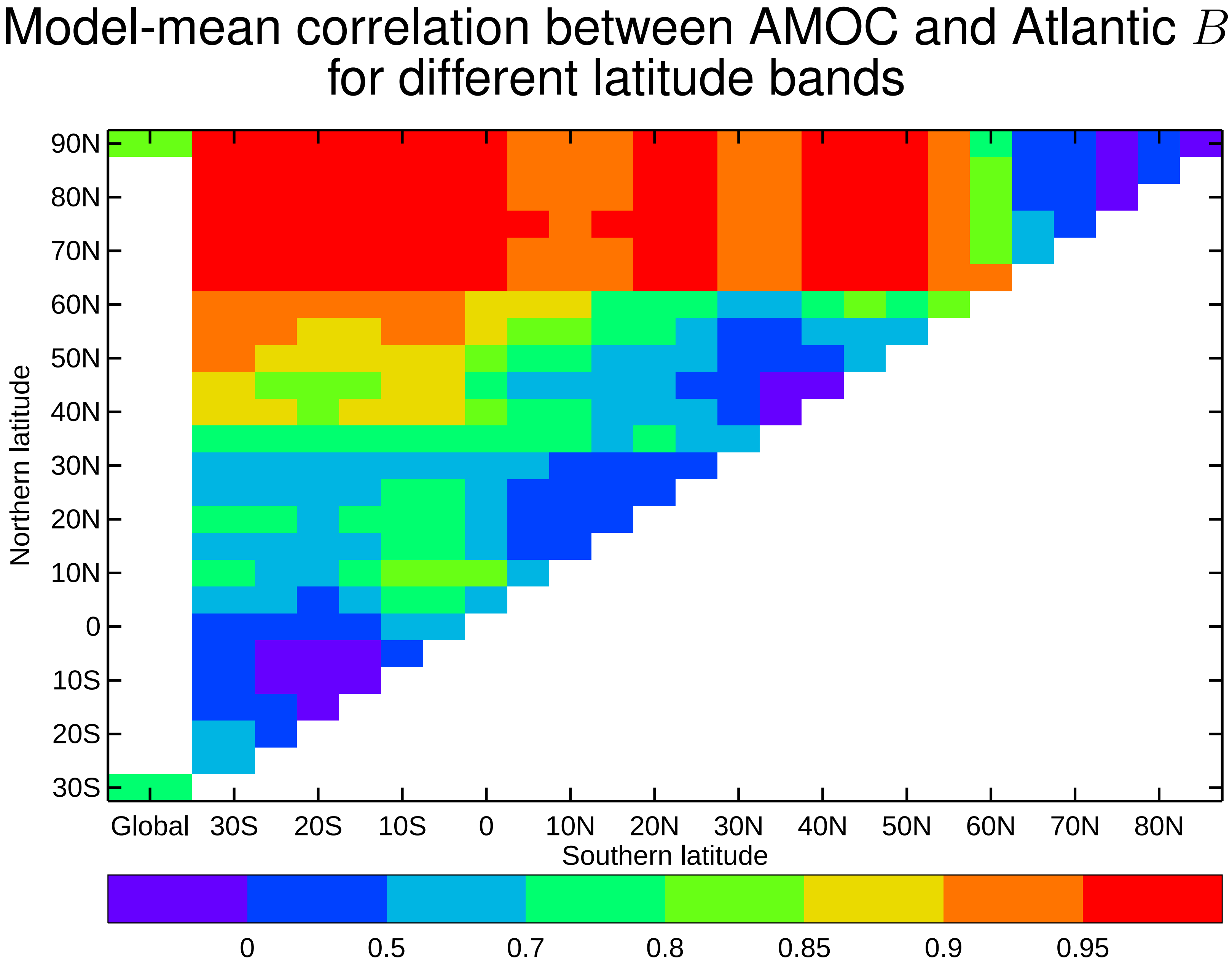


Change in $-\mathbf{u}_h \cdot \boldsymbol{\nabla}_h p$ in the Atlantic at 4 × CO_2



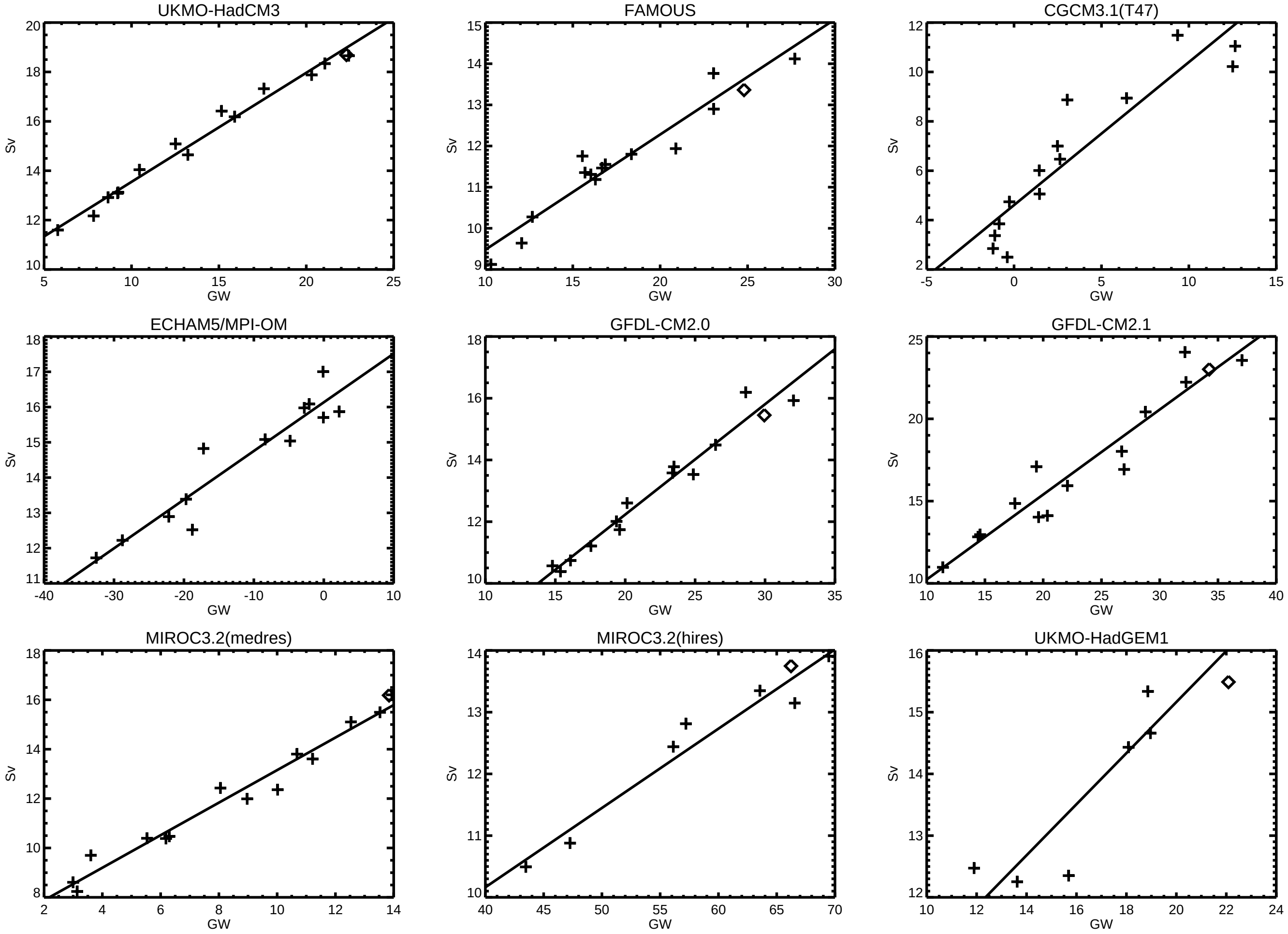
Relationship between AMOC and Atlantic B



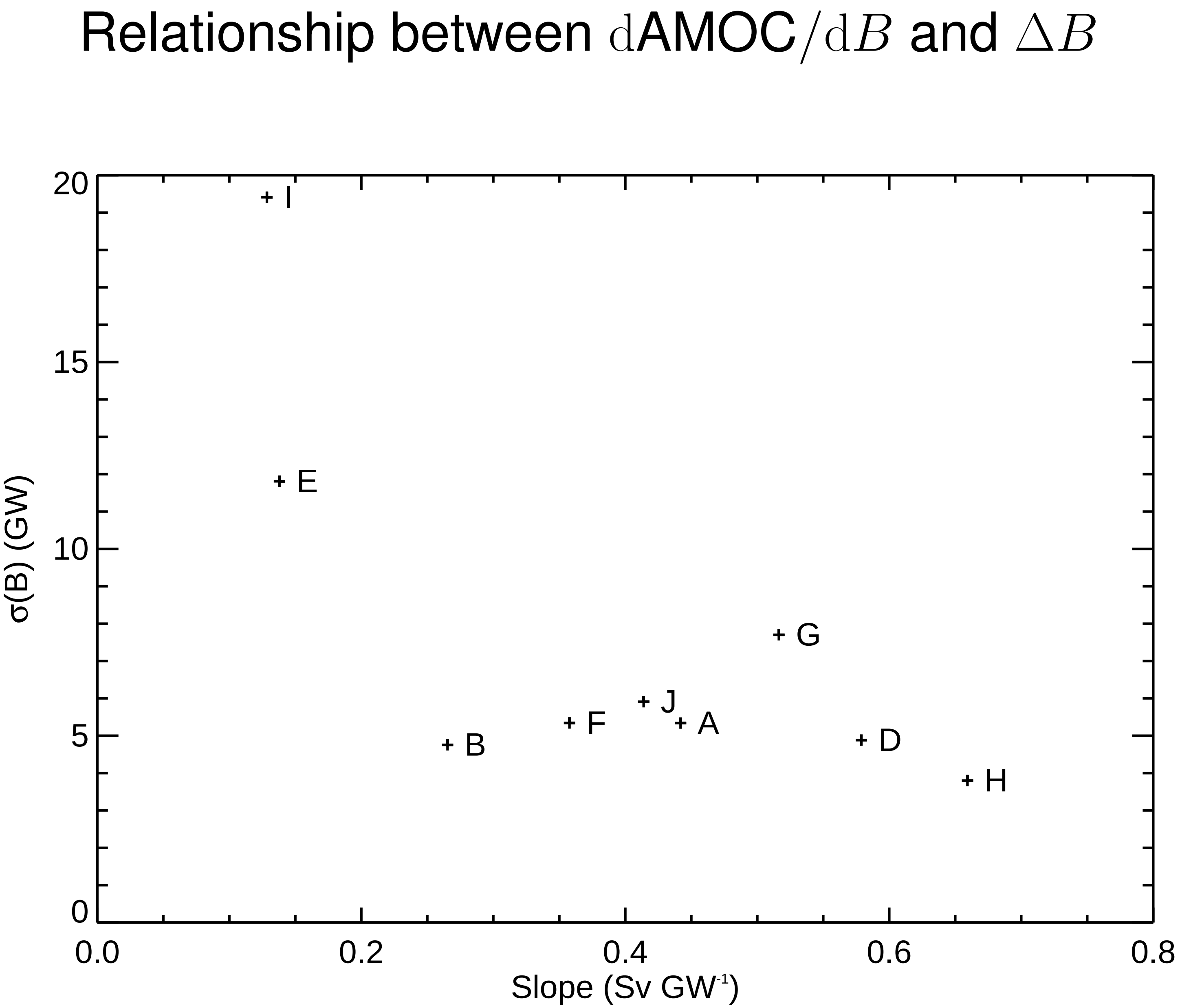


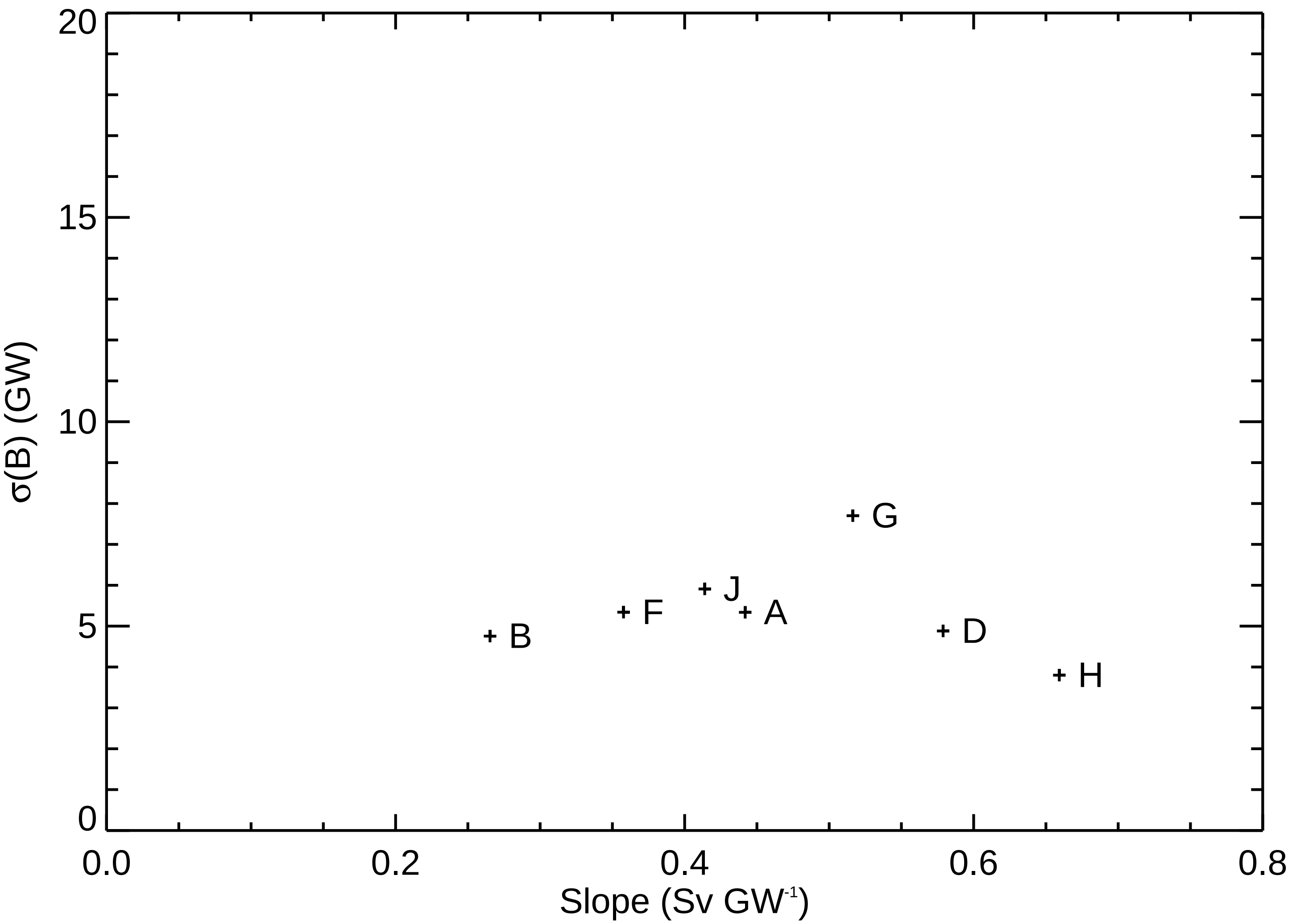
Model-mean correlation between AMOC and Atlantic B for different latitude bands

Relationship between AMOC and Atlantic B



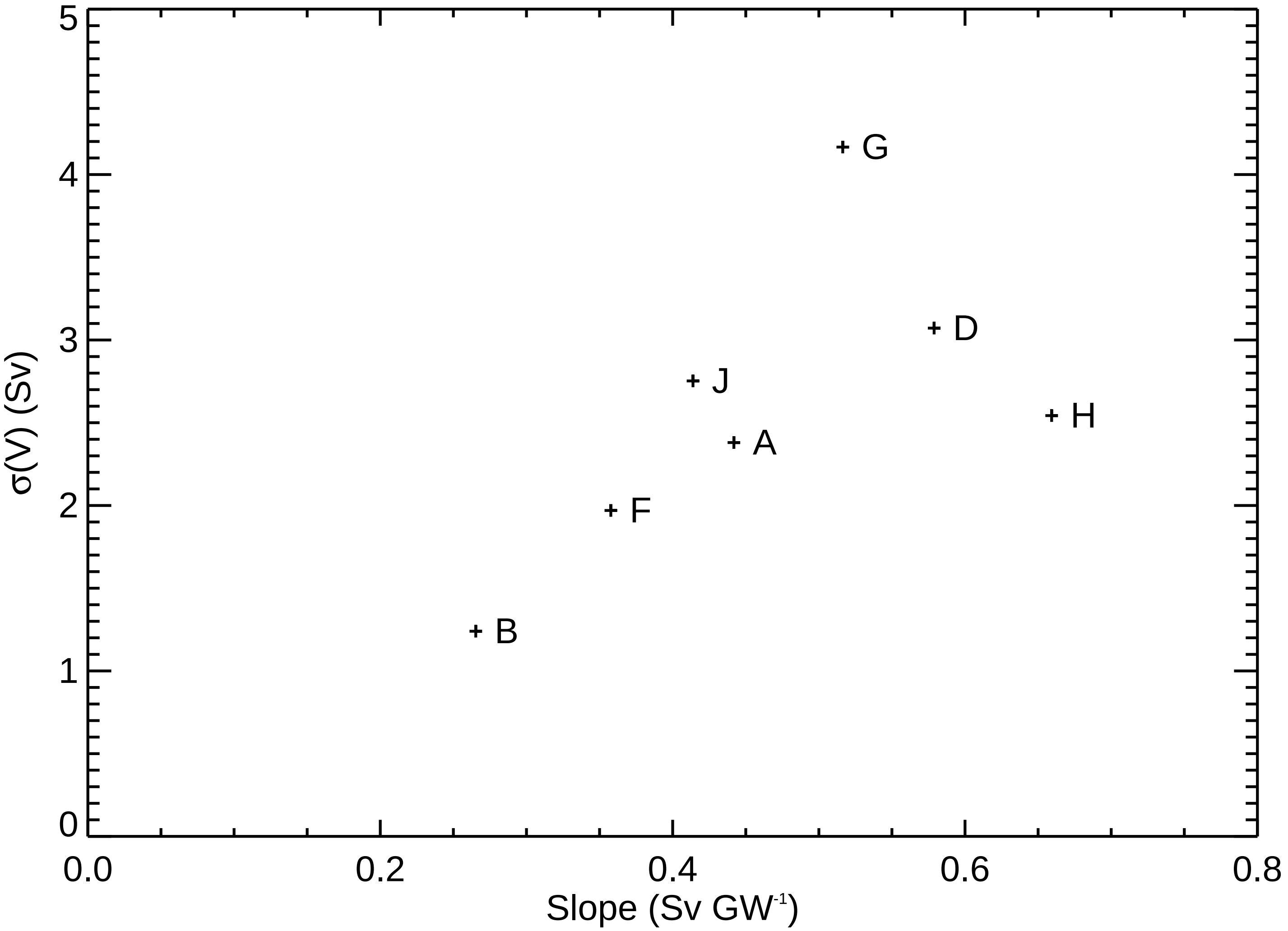
Spread of abscissa (ΔB) measures the buoyancy forcing, slope dAMOC$/\mathrm{d}B$ the ocean dynamical response.

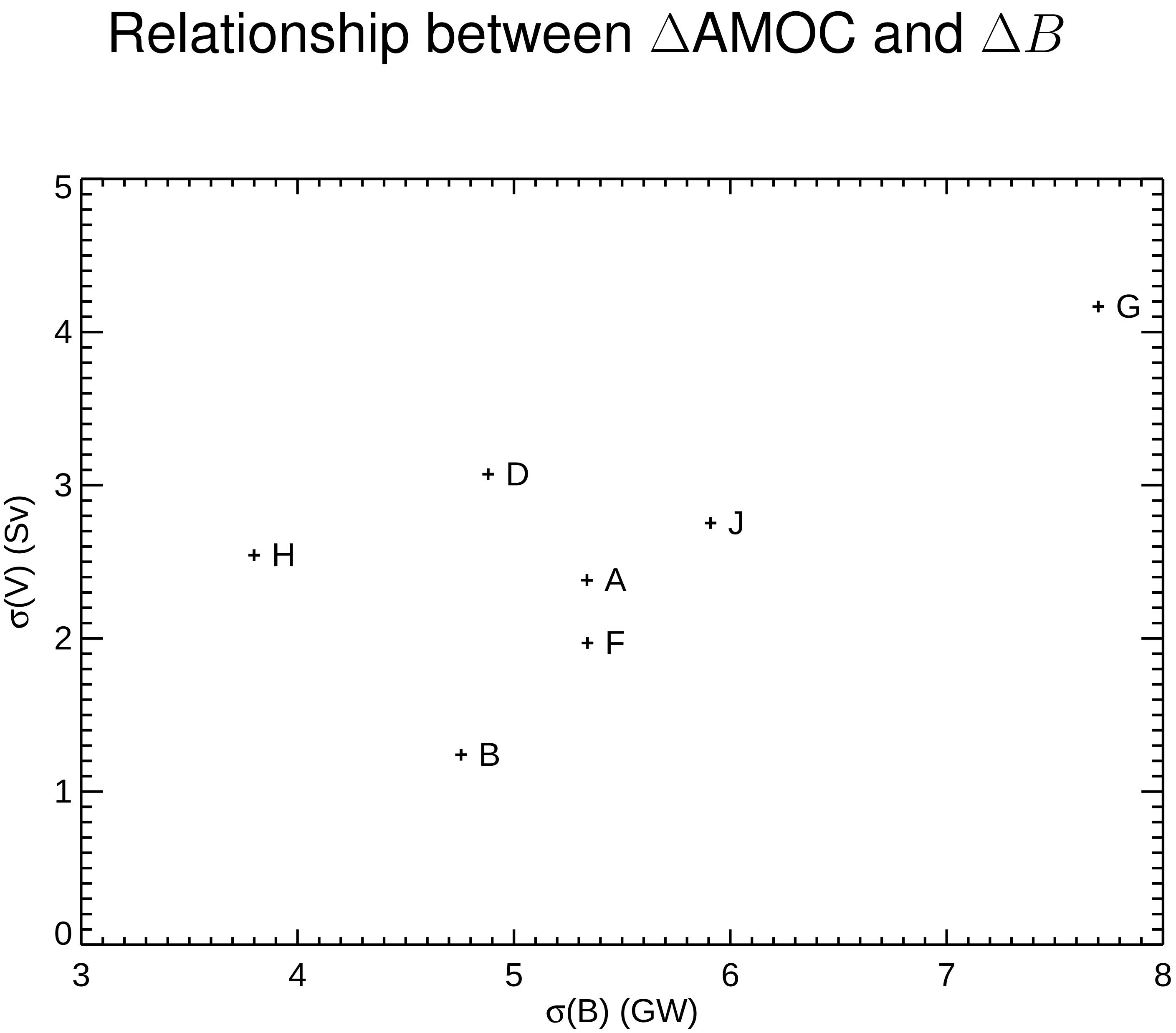

Relationship between dAMOC$/\mathrm{d}B$ and ΔB
σ(B) (GW)
Slope (Sv GW^{-1})
0
5
10
15
20
0.0
0.2
0.4
0.6
0.8
I
E
G
J
F
A
B
D
H



Relationship between dAMOC$/\mathrm{d}B$ and ΔB

Relationship between ΔAMOC and dAMOC$/\mathrm{d}B$





Relationship between ΔAMOC and ΔB

Conclusions

AOGCMs predict a weakening of the AMOC, with a large model uncertainty in the magnitude. This is believed to be a dynamical response to high-latitude buoyancy forcing of the Atlantic.

Considering the KE balance shows that work is done *against* $-\boldsymbol{\nabla}_h p$ on the global mean, but work is done *by* $-\boldsymbol{\nabla}_h p$ in the Atlantic, especially at high latitude.

The volume integral B of $-\mathbf{u}_h \cdot \boldsymbol{\nabla}_h p$ decreases in CO$_2$-increase experiments with several CMIP3 AOGCMs, and correlates well in time with the AMOC strength V.

The change ΔB in KE input during climate change is affected by buoyancy forcing, which changes the density field. ΔB is model-dependent and explains some of the spread in ΔAMOC.

The slope dAMOC$/\mathrm{d}B$ indicates the sensitivity of the AMOC to KE input. The slope is also model-dependent. Slopes are similar under SRES A1B forcing.

The KE budget may be a useful tool for analysis of AOGCMs, but we need a dynamical understanding as well.