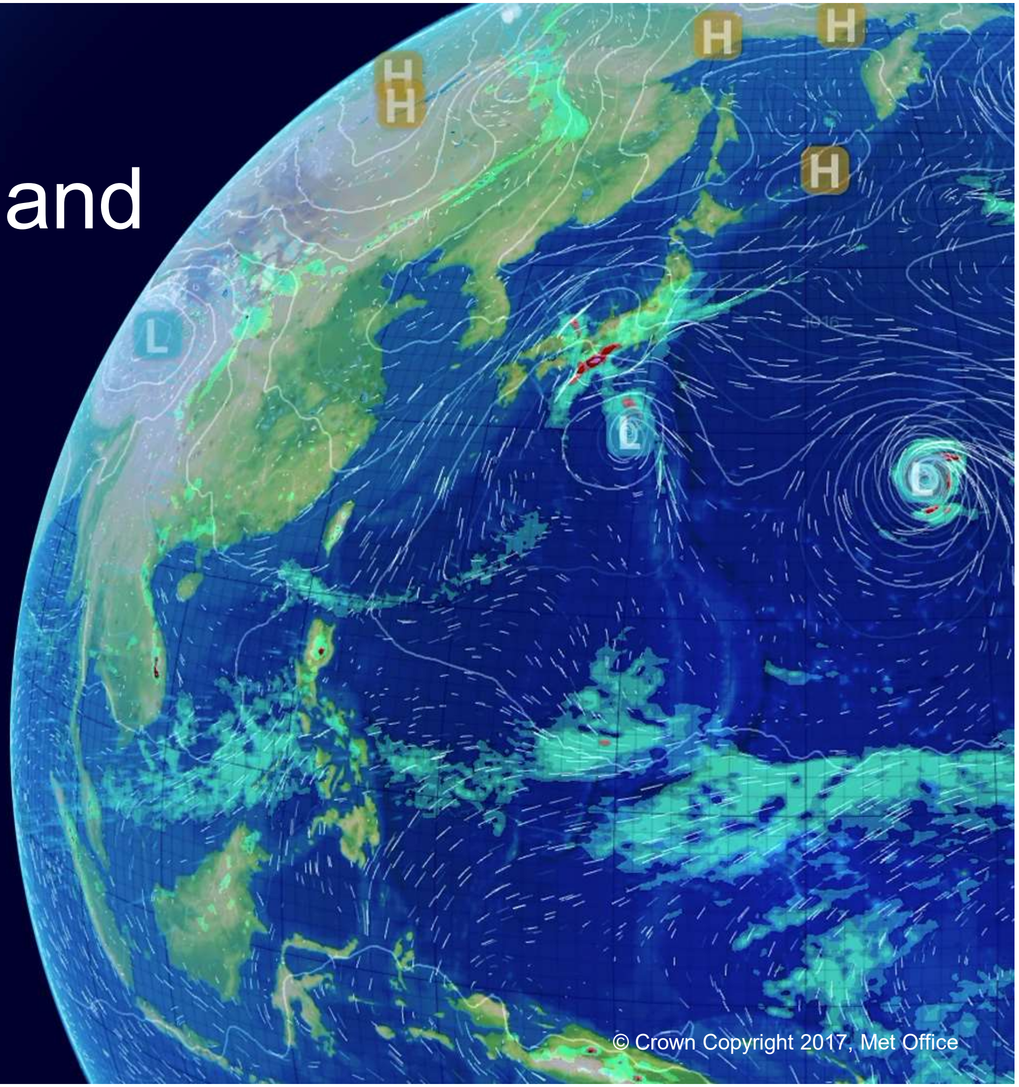
Met Office

# Net surface heat fluxes and Meridional Overturning Circulations

Mike Bell, Pat Hyder, Dave Storkey &
Richard Wood (Met Office)
Twm Jonathan, Helen Johnson,
David Marshall (Oxford University)

April 2021



Met Office

# Contents

- Aim, approach and motivation

- Net Surface Heat Fluxes (NSHF) in HadGEM3-GC3.1 coupled models

- Ideas based on models with simplified dynamics (following Gnanadesikan 1999, Nikurashin & Vallis 2011 & many other papers)

- Diagnostics
  - zonal integrals of NSHF and wind stress near the equator
  - potential temperature trends in (latitude, temperature) classes by basin
  - wedges of warm water next to eastern boundary in north Atlantic

- Summary

# Aim, approach & motivation

Aim: Develop simple conceptual pictures of MOC and OHU consistent with observations, numerical models and basic dynamical concepts

Approach: Use dynamical concepts and geographical patterns of net surface fluxes to develop hypotheses. Explore hypotheses using model diagnostics

Motivation: Anthropogenic ocean heat uptake is a perturbation of the Meridional Circulations

Met Office

# Contents

- Aim, approach and motivation
- Net Surface Heat Fluxes (NSHF) in HadGEM3-GC3.1 coupled models
- Ideas based on models with simplified dynamics (following Gnanadesikan 1999, Nikurashin & Vallis 2011 & many other papers)
- Diagnostics
  - zonal integrals of NSHF and wind stress near the equator
  - potential temperature trends in (latitude, temperature) classes by basin
  - wedges of warm water next to eastern boundary in north Atlantic

Met Office

# Annual mean Net Surface Heat Flux (NSHF) HadGEM3-GC3.1 N96ORCA1 (1950-2000)

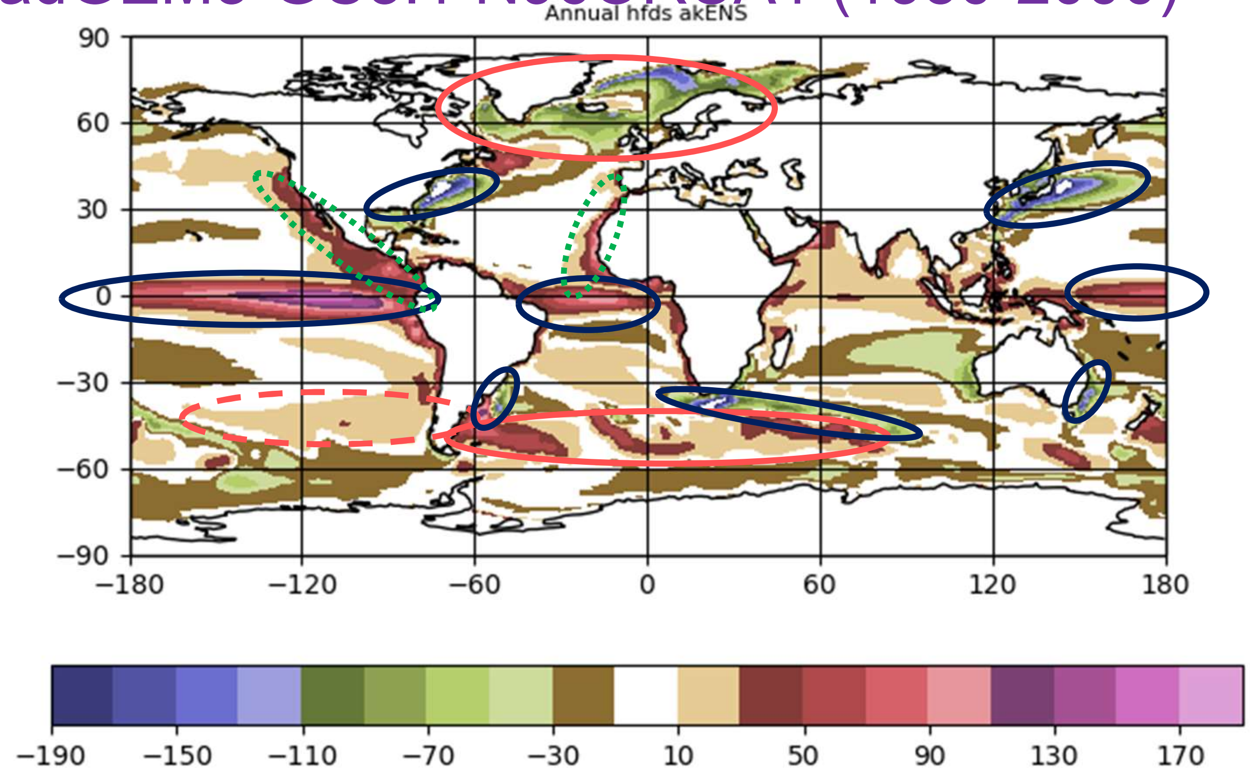
**Heat loss from N Atlantic**

**Heat flux into ocean in South Atlantic and Indian Ocean**

**Heat flux into ocean in equatorial basins**

**Heat loss from ocean in western boundary currents**

Coastal upwelling ? (eastern boundaries)

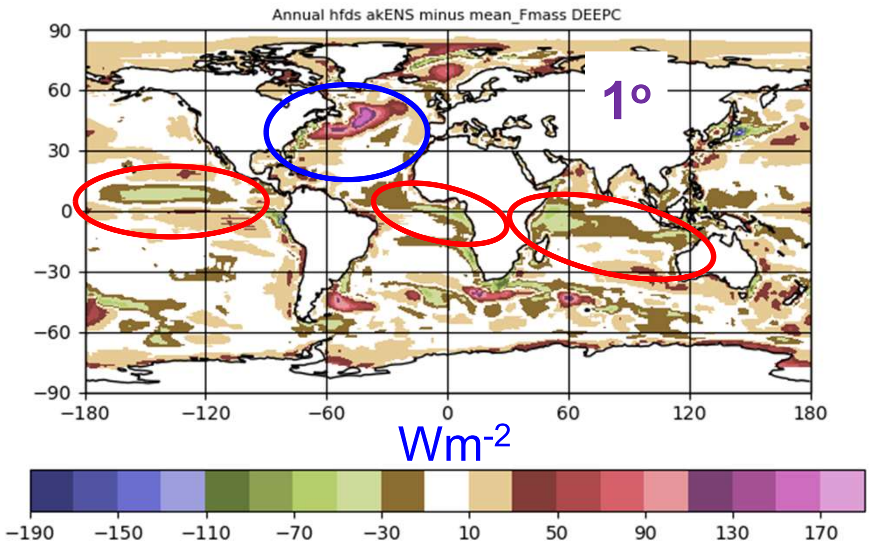


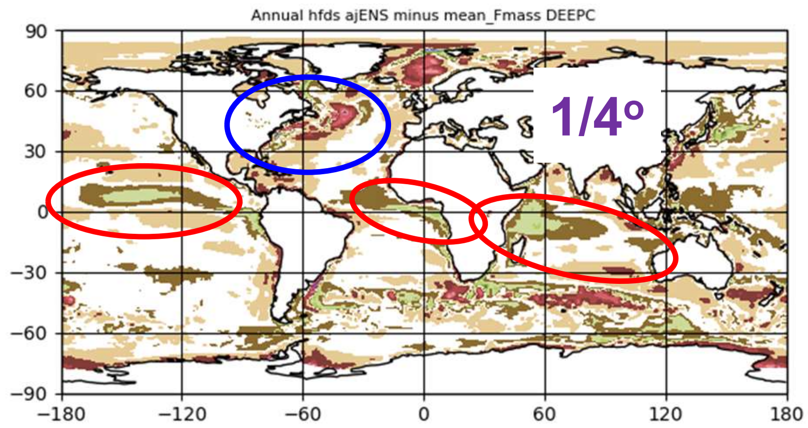

Net Surface heat flux ($Wm^{-2}$)

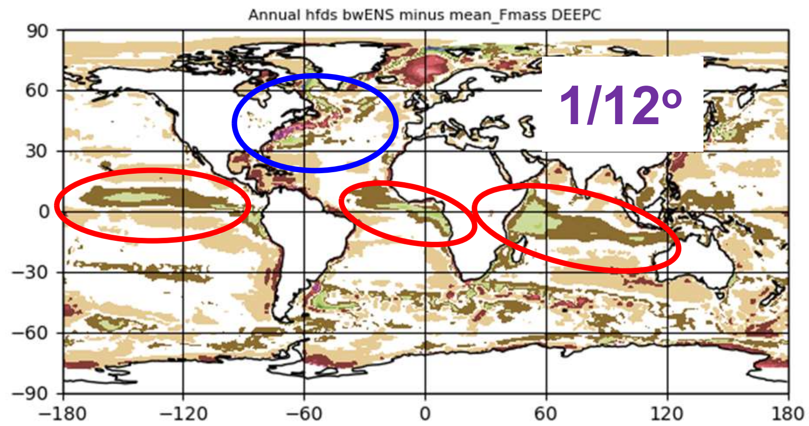
Met Office

# NSHF: historical GC3.1 simulations minus DEEPC (2000-2010)

DEEPC is based on ERAi & CERES data (Liu et al 2015)




- N96ORCA1 fluxes are quite “realistic”
- Differences in NW Atlantic reduce as model resolution improves
- Other differences (e.g. in equatorial regions) reduce less as resolution improves

Met Office

# Contents

- Aim, approach and motivation

- Net Surface Heat Fluxes (NSHF) in HadGEM3-GC3.1 coupled models

- Ideas based on models with simplified dynamics (following Gnanadesikan 1999, Nikurashin & Vallis 2011 & many other papers)

- Diagnostics
  - zonal integrals of NSHF and wind stress near the equator
  - potential temperature trends in (latitude, temperature) classes by basin
  - wedges of warm water next to eastern boundary in north Atlantic

# Ideas based on simplified dynamics

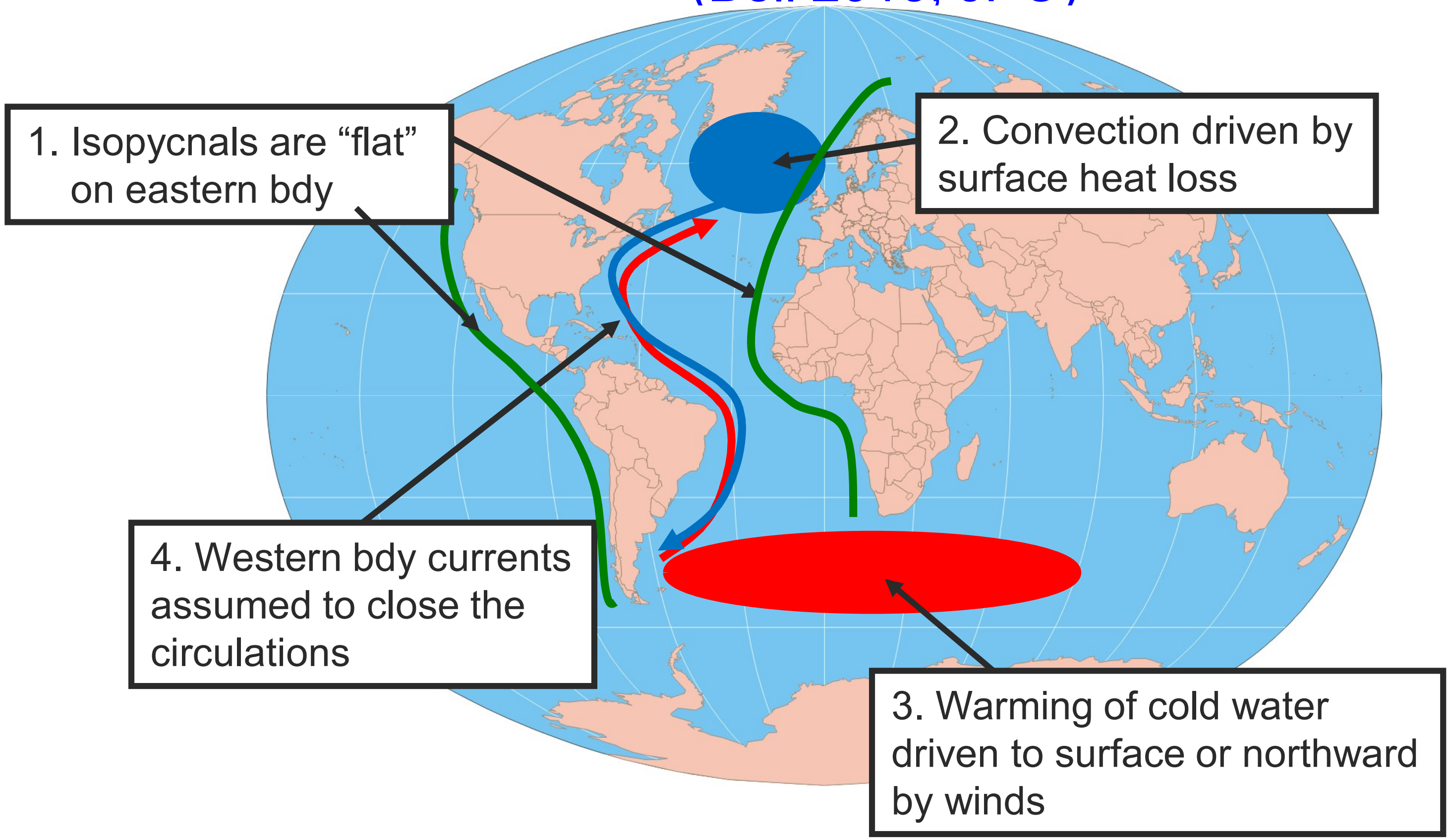
- Ekman "upwelling" driven by the winds supplies cold water that balances surface heating – see this both at the equator "as expected" (Large & Yeager 2009) and in the Southern Atlantic & Indian oceans

- Isopycnals are relatively flat along eastern boundaries (Veronis 1978)

- Western boundary currents advect warm water poleward; they supply heat that balances surface cooling (Dong & Kelly 2004, Tamsitt et al 2016)

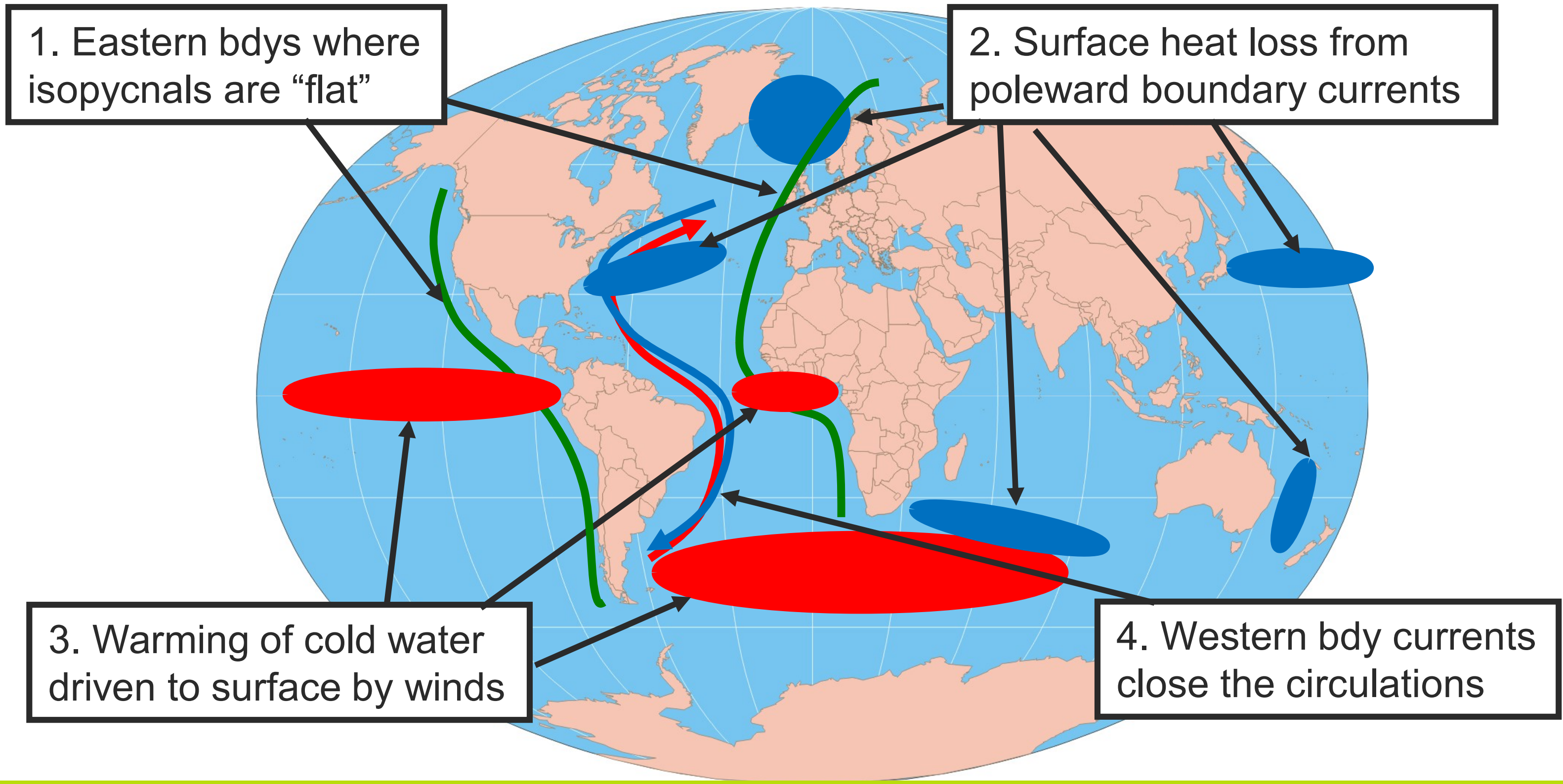
- In north Atlantic the deep thermocline on the eastern boundary results in a thermal wind shear flow in the north east Atlantic that supplies heat to balance surface cooling (Bell 2015)

# A simple dynamical model of the mid-depth MOC (Bell 2015, JPO)

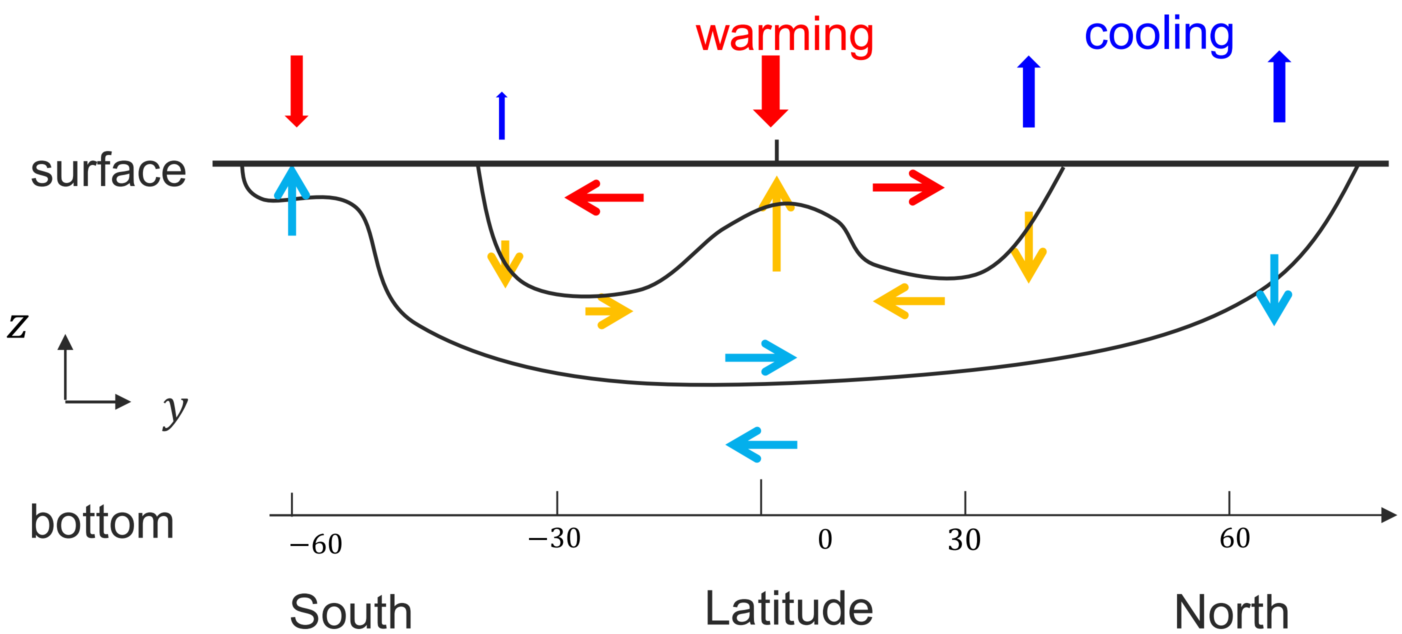


Met Office

# Extension to upper & mid-depth MOC cells



# Vertical section through upper & mid-depth MOC cells




Steady state circulations in layers of constant density driven by transformations of water between layers due to surface heat fluxes Walin 1982 Tellus

Met Office

# Contents

- Aim, approach and motivation

- Net Surface Heat Fluxes (NSHF) in HadGEM3-GC3.1 coupled models

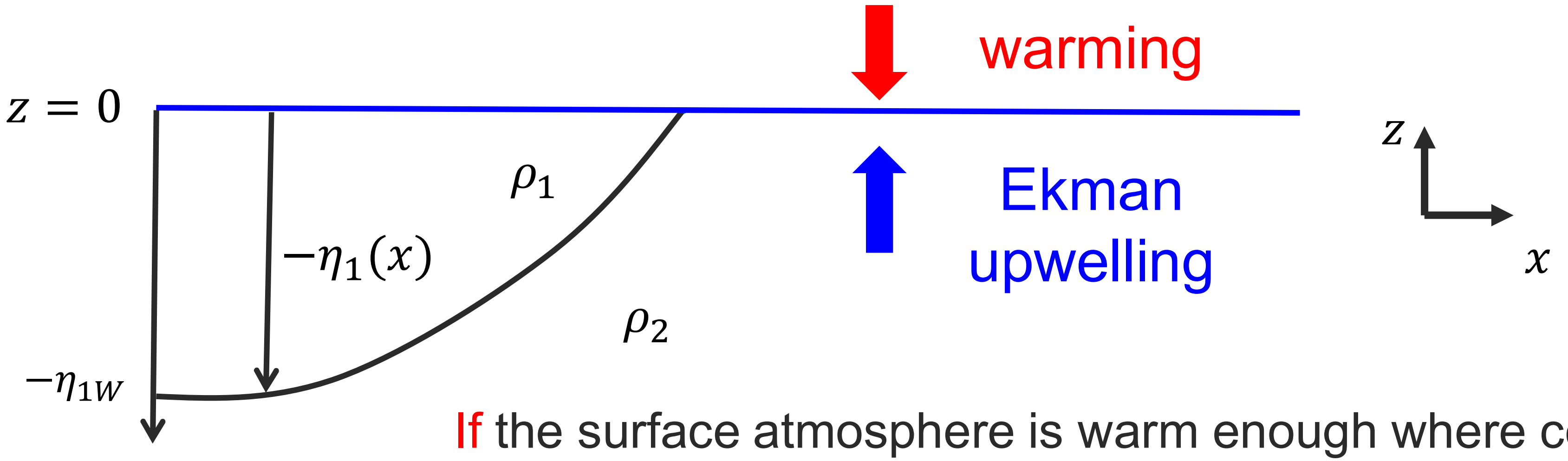
- Ideas based on models with simplified dynamics (following Gnanadesikan 1999, Nikurashin & Vallis 2011 & many other papers)

- Diagnostics
  - zonal integrals of NSHF and wind stress near the equator
  - potential temperature trends in (latitude, temperature) classes by basin
  - wedges of warm water next to eastern boundary in north Atlantic

Met Office

# Surface heat uptake in equatorial oceans

## Cross-section along equator

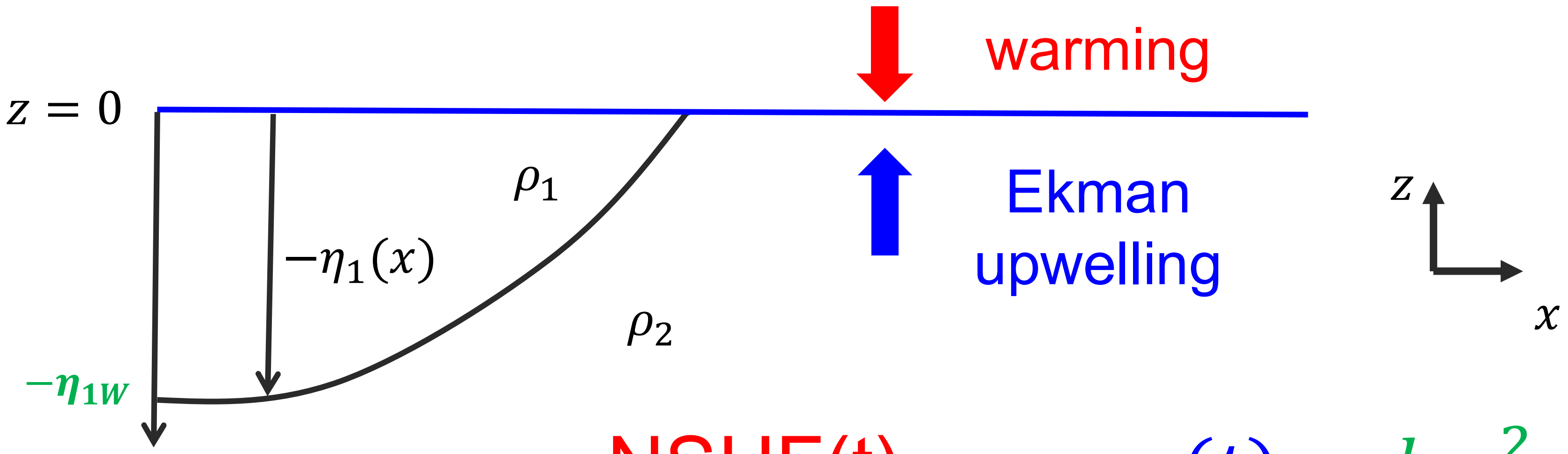



If the surface atmosphere is warm enough where cold deep water upwells to the surface

Then the rate of water mass transformation ($ms^{-1}$) is simply the Ekman upwelling velocity

Met Office

# Surface heat uptake in equatorial oceans




$$\mathrm{NSHF(t)} = -a\,\tau_x(t)\; - b\,\eta_{1W}^2(\mathrm{t})$$

NSHF for an area centred on equator

Zonally integrated wind stress "on" equator

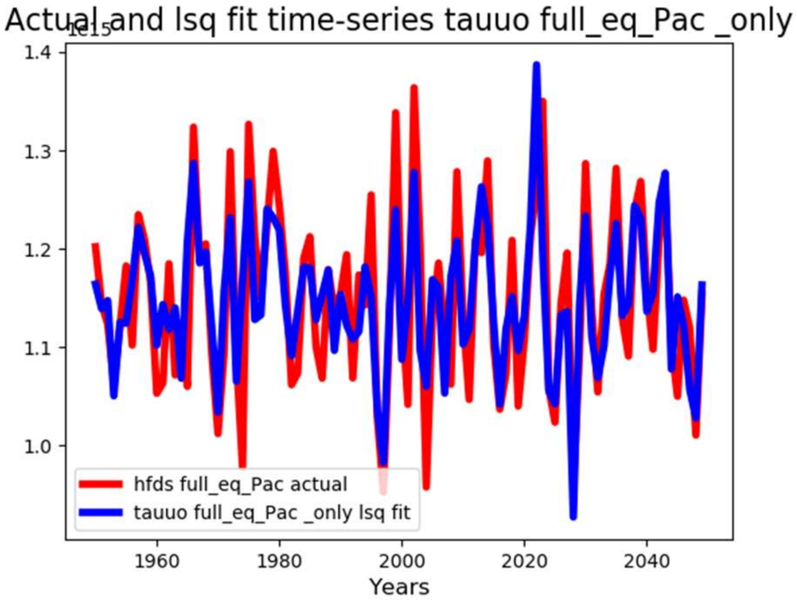
Met Office

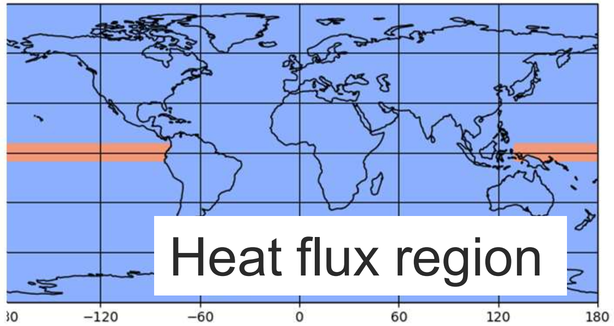
# Regression with time-series of annual means

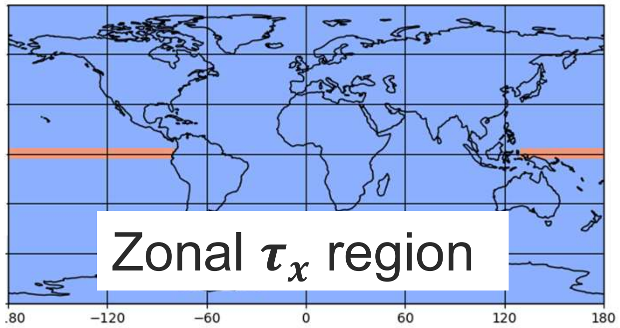
$$\mathrm{NSHF}(t) = -a\,\tau_x(t)$$

- Similar results obtained for 1°, 1/4° and 1/12° models (both for a and $r^2$)

- There are slightly higher correlations for 5-year running means




The heat flux averages 1·15 PW

$r^2 = 0{\cdot}65$

# Contents

- Aim, approach and motivation

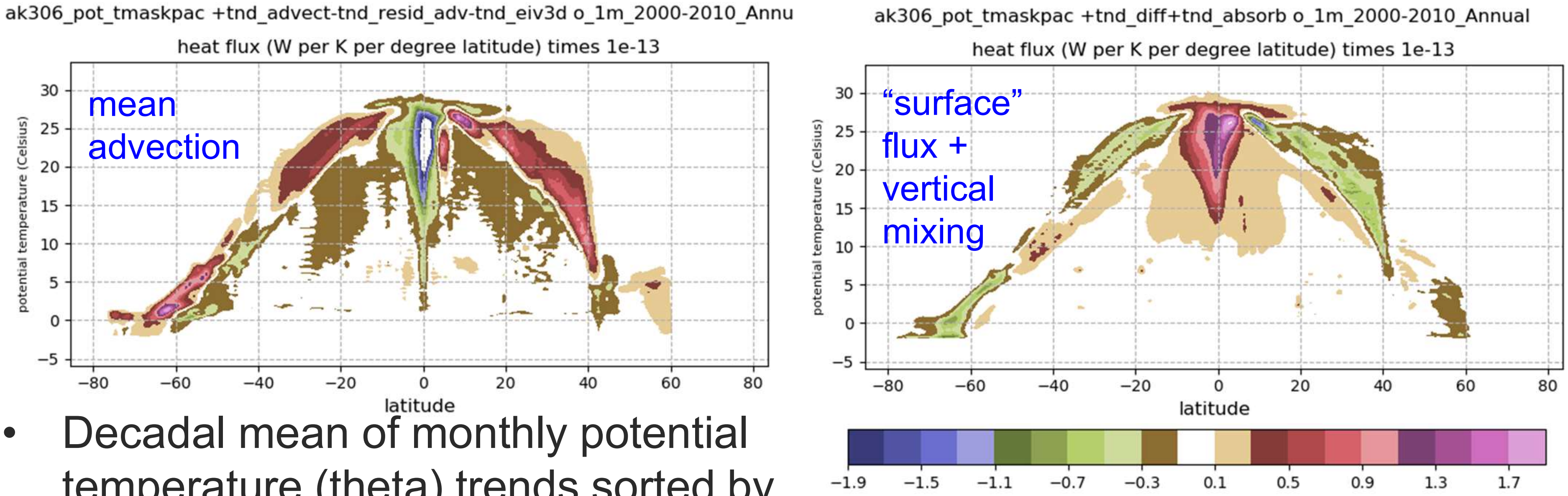
- Net Surface Heat Fluxes (NSHF) in HadGEM3-GC3.1 coupled models

- Ideas based on models with simplified dynamics (following Gnanadesikan 1999, Nikurashin & Vallis 2011 & many other papers)

- Diagnostics
  - zonal integrals of NSHF and wind stress near the equator
  - potential temperature trends in (latitude, temperature) classes by basin
  - wedges of warm water next to eastern boundary in north Atlantic

# Potential temperature tendencies in Pacific HadGEM3 N96O1 pre-industrial control

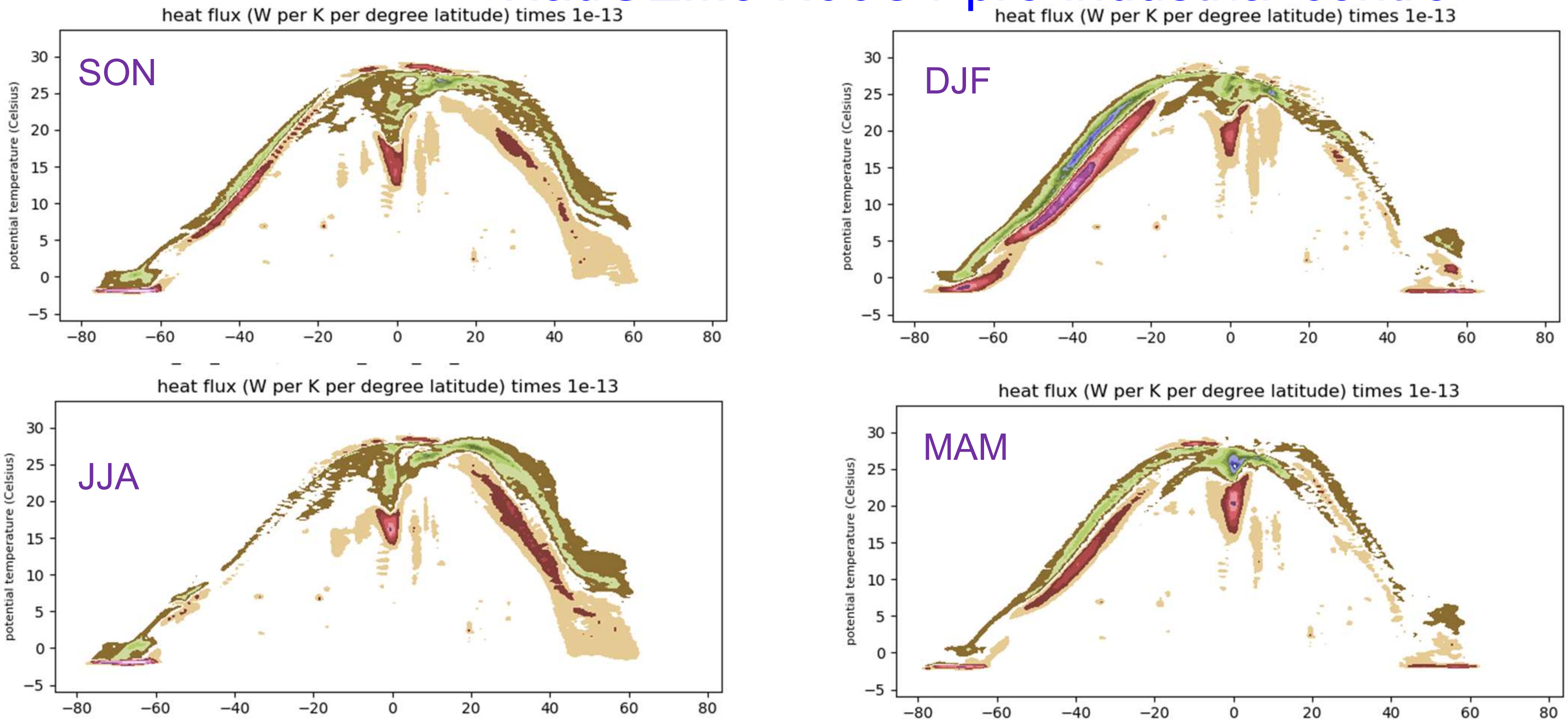
Met Office

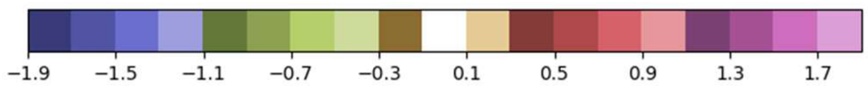



- Decadal mean of monthly potential temperature (theta) trends sorted by theta class and latitude
- Heat input by surface fluxes and vertical mixing is largely balanced by advection by time-mean fields: correlation is -0.88
- The vertical mixing varies greatly seasonally (next slide) – suggesting it is mainly related to mixing in the near surface mixed layer

Met Office

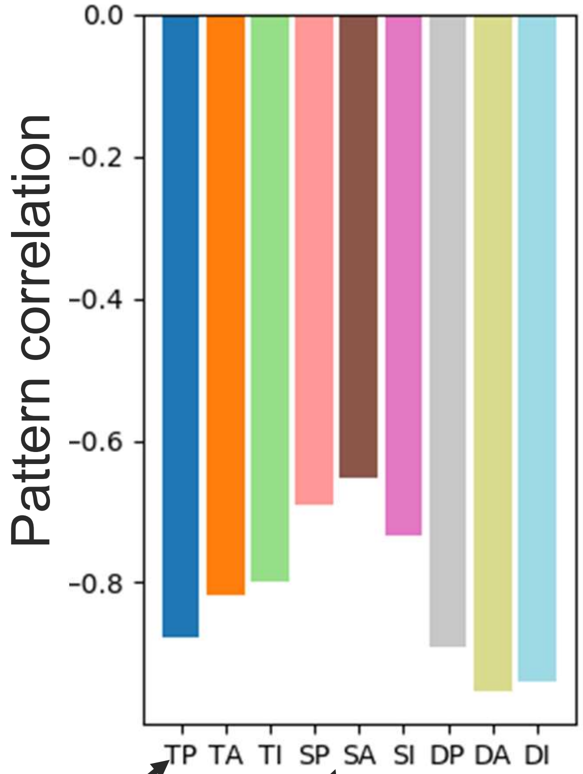
# Theta tendencies due to vertical mixing in Pacific HadGEM3 N96O1 pre-industrial control




**Note the dominance of seasonal variations**

# Pattern correlations by class and basin (N96O1)




- Pattern correlation is between changes due to:
  "surface" flux plus vertical mixing
and advection by the time-mean flow

- For different basins and data classes

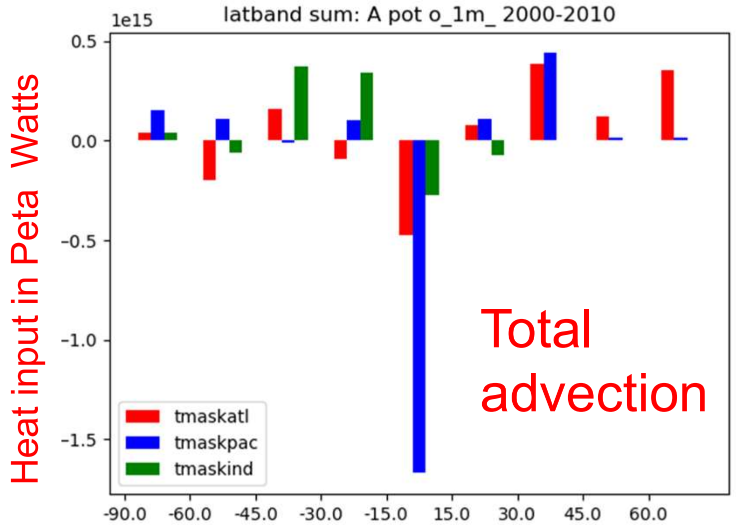
- The blue value for theta and the Pacific is -0.88,
(see the slide before last)

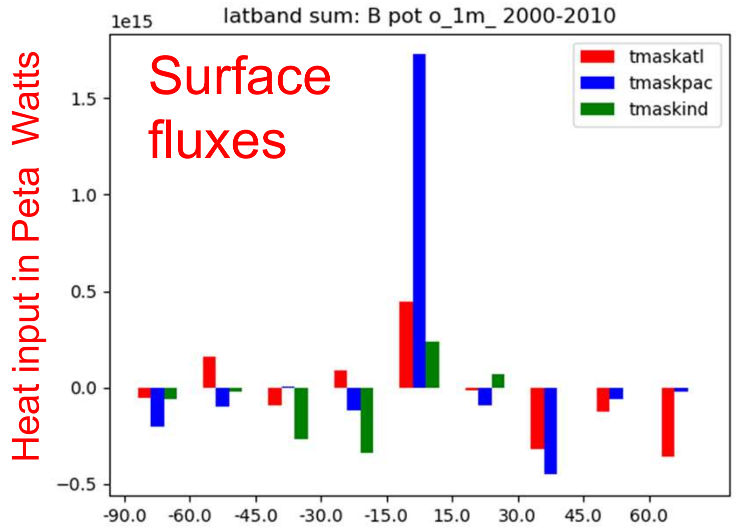
- Correlations for density (buoyancy) are largest, those for salinity are lowest

- Similar results are obtained for N216O025

T: Theta S: Salinity D: Density P: Pacific A: Atlantic I: Indian

# Fluxes by region/basin (N96O1)




- Heat input (PetaWatts) by latitude bands for Atlantic, Pacifc and Indian basins
- Equatorial Pacific dominates heat uptake. Heat is lost in Atlantic & Indian basins
- Vertical diffusion makes no contribution to these latitude band sums

# Contents

- Aim, approach and motivation

- Net Surface Heat Fluxes (NSHF) in HadGEM3-GC3.1 coupled models

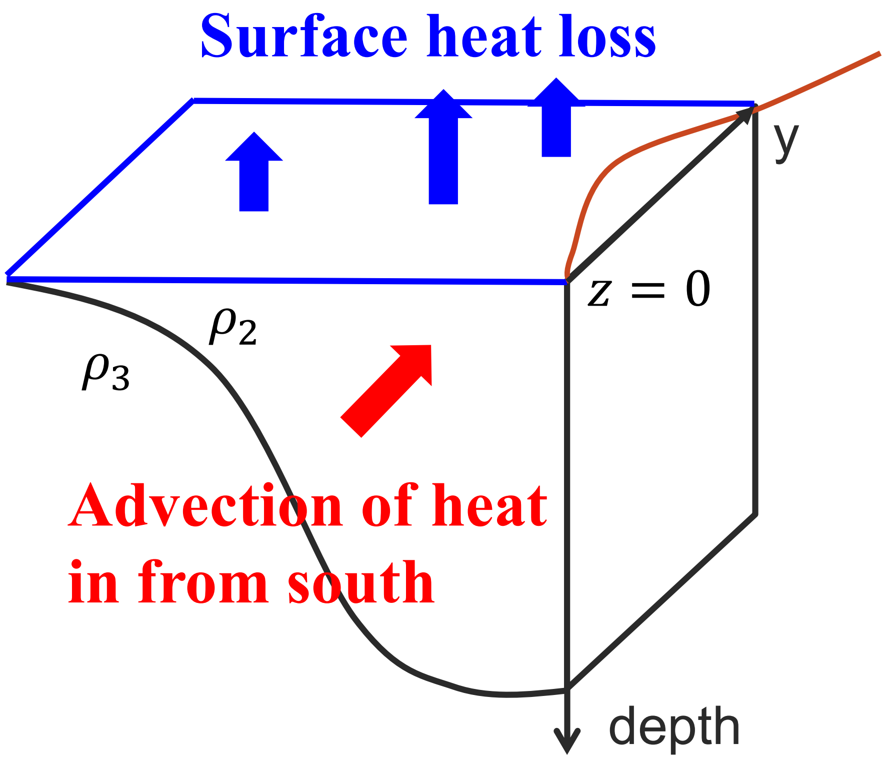
- Ideas based on models with simplified dynamics (following Gnanadesikan 1999, Nikurashin & Vallis 2011 & many other papers)

- Diagnostics
  - zonal integrals of NSHF and wind stress near the equator
  - potential temperature trends in (latitude, temperature) classes by basin
  - wedges of warm water next to eastern boundary in north Atlantic

Met Office

# Hypothesis for heat loss in N Atlantic

- The isopycnals are relatively flat on the eastern boundary
- In the north Atlantic the water near the eastern bdy is warm and salty
- At latitudes of sub-polar gyre the wind raises isopycnals to the west
- Thermal wind balance then implies a northward surface flow at 50°N
- The flow of heat through this "southern face" is lost to the atmosphere

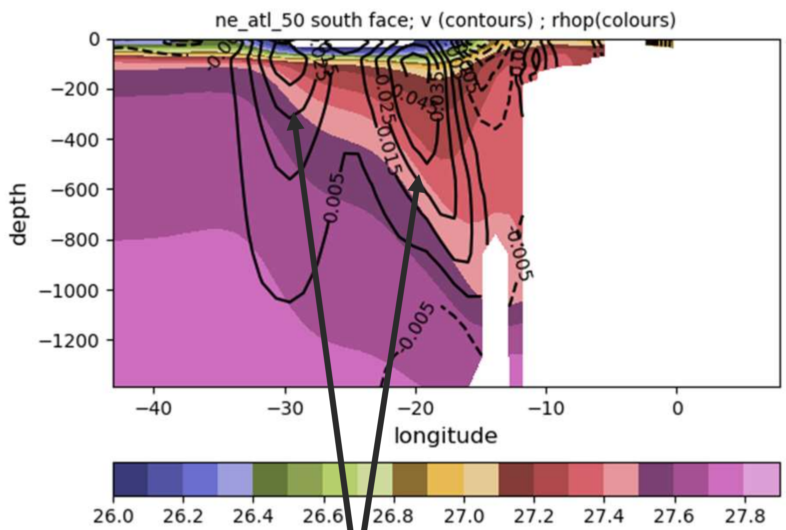


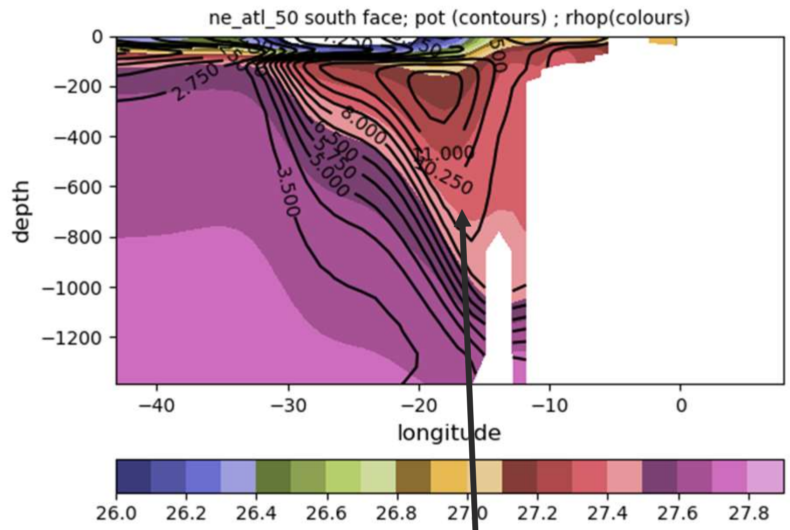
# Cross-section at 50°N near Atlantic eastern boundary

Annual mean N96O1 pre-industrial simulation

Velocity (lines); density (colours)

Pot temp (lines) & density



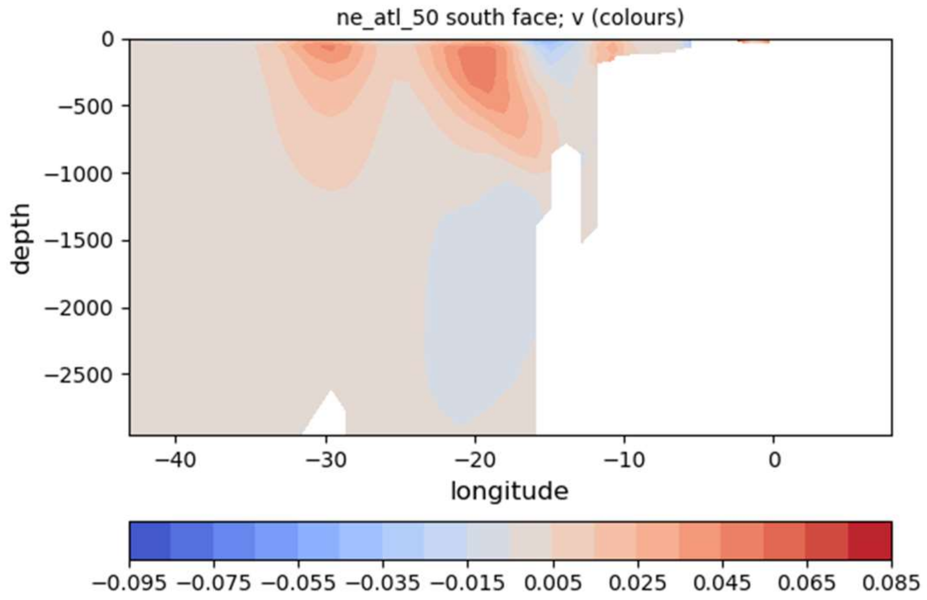

Northward currents where isopycnals slope steeply

Wedge of warm water extends to 800 m depth!

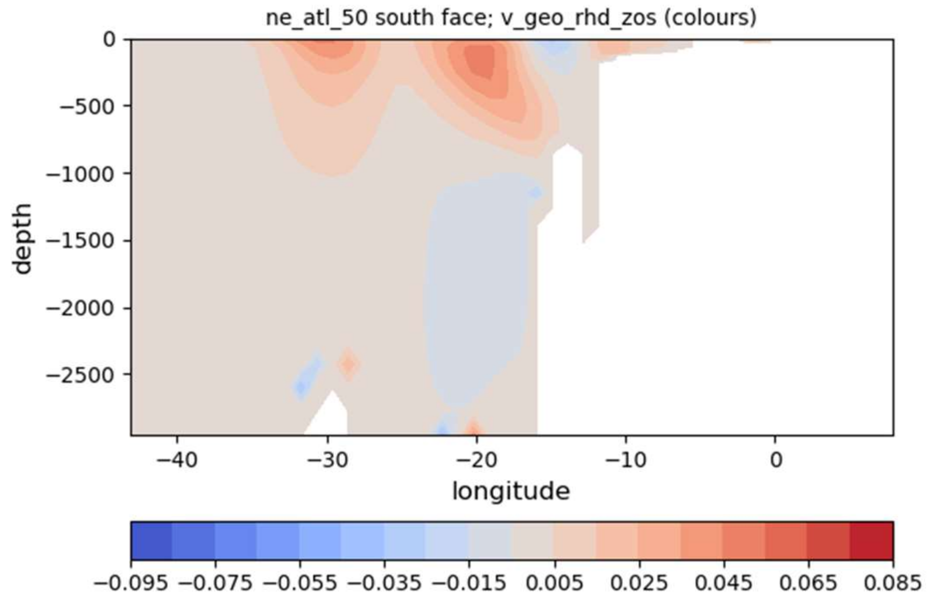
# Cross-section at 50ºN near Atlantic eastern boundary

## Annual mean N96O1 pre-industrial simulation

### Full velocity




### Geostrophic and reduced gravity at 800 m




- Good agreement between full velocity and that calculated from “thermal wind” shear

Met Office

## What sets the depth of the wedge on the eastern boundary? Gnanadesikan (1999)

- Water mass transformations:
  - cold to warm depends on zonal mean wind stress in Southern Ocean
  - warm to cold depends on square of depth of thermocline

- A shallow thermocline deepens until transformation rates become equal

- This idea has been used in idealized studies of Ocean Heat Uptake (Johnson et al 2007, Marshall & Zanna 2014)

Met Office

# Summary

- Geographical patterns of annual mean Net Surface Heat Fluxes (NSHF) in HadGEM3 GC3.1simulations appear to agree well with:
  - DEEPC analysis based on CERES satellite & ERA-interim data
  - “simple” ideas of wind driven water mass transformations
- Zonal integral of annual mean wind stress along the equator in Pacific is strongly correlated with zonal integral of annual mean net surface heat flux
- Water mass transformations in (temperature, latitude) space by advection by the time-mean flow and surface fluxes modified by near surface mixing are strongly anti-correlated
- Idea of a wedge of warm, salty water near eastern boundary in north Atlantic giving rise to flow of warm water into the north-east Atlantic is consistent with a HadGEM3 GC3 N96O1 pre-industrial simulation

# References


Bell, M. J. 2015 Meridional overturning circulations driven by surface wind and buoyancy forcing. J. Phys. Oceanogr., 45, 2701–2714, doi: 10.1175/JPO–D–14–0255.1.

Dong, S., and K. A. Kelly, 2004: Heat budget in the Gulf Stream region: The importance of heat storage and advection. J. Phys. Oceanogr., 34, 1214–1231, doi:10.1175/1520-0485(2004)034,1214:HBITGS.2.0.CO;2.

Gnanadesikan, A., 1999: A simple predictive model of the structure of the oceanic pycnocline. Science, 283, 2077–2081.

Johnson, H. L., D. P.Marshall, and D. A. J. Sproson, 2007: Reconciling theories of a mechanically driven Meridional Overturning Circulation with thermohaline forcing and multiple equilibria. Clim. Dyn., 29, 821–836.

Large, W. G., and S. G. Yeager 2009: The global climatology of an interannually varying air–sea flux data set. Climate Dyn., 33, 341–364, https://doi.org/10.1007/s00382-008-0441-3.

Liu, C. Allan, R. P., P. Berrisford , M. Mayer , P. Hyder, N. Loeb , D. Smith , P.-L. Vidale, J. Edwards (2015) Combining satellite observations and reanalysis energy transports to estimate global net surface energy fluxes 1985-2012, J. Geophysical Research, doi: 10.1002/2015JD023264

Marshall, D. P., and L. Zanna, 2014: A conceptual model of ocean heat uptake under climate change. J. Clim., 26,22, 8444-8465, doi:10.1175/JCLI–D–13–00 344.1.

Nikurashin, M., and G. Vallis, 2011: A theory of deep stratification and overturning circulation in the ocean. J. Phys. Oceanogr., 41, 485–502, doi:10.1175/2010JPO4529.1.

Tamsitt, V. L. D. Talley, M. R. Mazloff and I. Cerovecki 2016 Zonal Variations in the Southern Ocean Heat Budget. J. Clim., 29, 6565-6579. DOI: 10.1175/JCLI-D-15-0630.1

Veronis, G., 1978: Model of World Ocean circulation: III. Thermally and wind driven. J. Mar. Res., 36, 1–44.

Walin, G., 1982: On the relation between sea-surface heat flow and thermal circulation in the ocean. Tellus, 34, 187–195.