MERIDIONAL OVERTURNING CIRCULATION: SOME BASICS AND ITS MULTI-DECADAL VARIABILITY

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OUTLINE:
- Describe thermohaline and meridional overturning circulations,
- Multi-decadal variability in the North Atlantic as depicted by the Atlantic Meridional Overturning Circulation (AMOC),
- Examples of climate impacts and potential predictability,
- Results from the NCAR Community Climate System Model (CCSM3) simulations,
- Summary
WHAT IS THERMOHALINE CIRCULATION (THC)?

It is that part of the ocean circulation which is driven by density differences (as opposed to wind and tides).

Because the ocean density is a function of temperature (thermo) and salinity (haline), this circulation is referred to as the thermohaline circulation and indicates a driving mechanism.

These density differences are primarily caused by surface fluxes of heat and freshwater and subsequent interior mixing.

The oceanic density distribution is itself affected by the currents and associated mixing. Thermohaline and wind driven currents interact with each other, and therefore cannot be truly separated.

THC IS NOT AN OBSERVATIONALLY MEASURABLE QUANTITY!
THERMOHALINE CIRCULATION PATHWAYS
"CONVEYOR BELT"

While temperature acts as the driver, salinity provides the break!
**WHAT IS MERIDIONAL OVERTURNING CIRCULATION (MOC)?**

It is a related field, referring to a streamfunction on the depth-latitude plane. It can be obtained from

\[
\Psi(y, z, t) = \int_{z}^{0} dz \int_{west}^{east} V(x, y, z, t) dx
\]

where

- \(x\): longitudinal (zonal) direction (+ve eastwards)
- \(y\): latitudinal (meridional) direction (+ve northwards)
- \(z\): height (+ve upwards)
- \(t\): time
- \(V\): meridional velocity component

This field is often used in the modeling community, because it is easy to diagnose.

**MOC INCLUDES WIND-DRIVEN CIRCULATION!**
MERIDIONAL OVERTURNING CIRCULATION

GLOBAL

ATLANTIC

ANTARCTIC BOTTOM WATER (AABW)

Units: Sverdrup

(Wind Driven)

NORTH ATLANTIC DEEP WATER (NADW)

(\textit{Sv} = 10^6 \text{ m}^3 \text{s}^{-1})
MERIDIONAL OVERTURNING CIRCULATION

Depth - Latitude Plane

Density - Latitude Plane

in Sv
OCEANIC NORTHWARD HEAT TRANSPORT

Trenberth and Caron (2001)
WHAT DRIVES THC / MOC?

MECHANISM I: Cooling at high latitudes. For steady state, downward penetration of heat by mixing is necessary.

Turbulent mixing supplies energy.
WHAT DRIVES THC / MOC?

MECHANISM II: Westerly winds over the Southern Ocean. No meridional flow can be supported at intermediate depths at the latitude band of the Drake Passage due to lack of topographic barriers that can support east-west pressure gradients.

\[-fV = -\frac{1}{\rho} \frac{\partial p}{\partial x}\]

Winds directly supply energy.
Many coupled general circulation models (CGCMs) exhibit multi-decadal or longer time scale (20 - 100+ years) variability in their AMOCs.

Time series of the AMOC maximum from CCSM3 present-day control simulations

Bryan et al. (2006, J. Climate)
HEAT CONTENT CHANGES between mid-1990s and mid-1950s
(CCSM3 20th Century simulations - 1870 control integration)

Gent et al. (2006, J. Climate)
CHANGE IN SOME FIELDS BETWEEN HIGH AND LOW AMOC PERIODS IN THE GFDL CM2.1 CONTROL SIMULATION

Rainfall (cm day\(^{-1}\))

Vertical shear of zonal wind (m s\(^{-1}\))

Vertical shear computed for 300 hPa - 850 hPa.

Tom Delworth
AMOC IN THE 20th CENTURY ENSEMBLE INTEGRATIONS

Max. NH Atlantic Overturning ( 3 pt. smooth)

Frank Bryan
Time series of AMOC maximum from 5 members of a 30-member ensemble of CCSM3 (T42x1) A1B scenario simulations
TIME SERIES OF NORTH ATLANTIC MOC AT 25°N

Bryden et al. (2005)

RAPID Array
(4-35 Sv)
ATLANTIC MULTI-DECADAL OSCILLATION (AMO)

AMO INDEX (SST, °C)

SST vs AMO INDEX REGRESSION (°C/SD)

Sutton & Hodson (2005)

Trenberth & Shea (2006)
Since Delworth et al. (1993) study, there is a broad consensus that the density anomalies in the “sinking region” of the AMOC drives this variability.

However, many fundamental questions still remain largely unanswered:

- mechanism [nature of this mode, role of atmospheric variability],
- robustness of mechanism,
- time-scale,
- implications for initialization (and predictability),
- implications for our assessments of 20\textsuperscript{th} century, future scenario, etc. climates,
- ......
AMOC IN CCSM3 T85x1 RESOLUTION, PRESENT-DAY CONTROL SIMULATION

Danabasoglu (2008, J. Climate)
SEA SURFACE TEMPERATURE (SST)

SST EOF1 (var=24.3%)

SST EOF1 TIME SERIES

AMOC-SST PC1 CORRELATION

99%

AMOC lagging  AMOC leading

LAG (year)
NORTH-SOUTH GYRE BOUNDARY FLUCTUATION and WIND STRESS CURL SIMULTANEOUS REGRESSION
MARCH-MEAN BOUNDARY LAYER DEPTH (BLD)

BLD and AMOC PC1 time series

99% AMOC leading
AMOC lagging

DENSITY REGRESSIONS WITH AMOC PC1 TIME SERIES

a) LABRADOR SEA REGION

AMOC lagging
AMOC leading

CORRELATION FUNCTION

AMOC leading

BLD EOF1 (var=44.4%)
WIND STRESS CURL

WSC EOF1 (var=25.7%)

WSC_EOF1 POWER SPECTRUM

95%  99%

x10^{-8} N m^{-3}

95%  99%
SUMMARY

• Although they refer to different concepts, THC and MOC are often used as synonyms.

• There are no long-term observational estimates of the MOC transport.

• Many CGCMs exhibit multi-decadal or longer time scale variability in their AMOCs.

• This variability is usually associated with variations in the ocean heat transport, ocean heat content, North Atlantic SSTs (e.g. AMO), climate changes over North America, Western Europe, and Africa.

• There are indications of potential predictability.
IN CCSM3 T85x1 RESOLUTION, PRESENT-DAY SIMULATION:

• This multi-decadal variability shows rather large amplitudes in both AMOC and SST. Comparisons of the latter with observations indicate that neither the pattern nor the magnitude of the SST anomalies is realistic. However, the role of the mean-state biases remains unclear.

• These SST anomalies are created by the fluctuations of the subtropical -subpolar gyre boundary driven by small scale WSC anomalies.

• The present results do not support an ocean mode that relies on a phase lagged relationship between temperature and salinity in their contributions to the total density in the model’s associated deep water formation region.

• Atmospheric variability associated with the model’s NAO appears to play a prominent role in maintaining this variability.

• It is likely that the processes setting the 21-year time scale have oceanic origins.
ATLANTIC NORTHWARD HEAT TRANSPORT (NHT)

a) TIME-MEAN NHT

b) NHT vs MOC EOF1 REGRESSION

PW / AMOC PC1 variance
LABRADOR SEA ADVective HEAT FLUX REGRESSIONS WITH AMOC PC1 TIME SERIES
OBS: Levitus et al. (1998) & Steele et al. (2001)

MEAN SST BIAS

BAROTROPIC STREAMFUNCTION

Sv
SIMPLIFIED DIAGRAM OF PHASE RELATIONSHIPS

negative NAO

- min AMOC
- reduced sea-ice cover,
- increased surface heat loss,
- increased upwelling of salt

positive NAO

- strong subpolar gyre
- max AMOC
- “max” SST
- increased sea-ice cover,
- reduced surface heat loss,
- reduced upwelling of salt,
- diffusive fluxes