Introduction

The properties of water masses in the ocean are set by air-sea interactions at the surface and convective overturning. As direct transfer of heat and salt to the deep ocean is not possible, to first-order approximation these properties do not change when in the interior ocean water masses are advected. The pathways followed by the water masses connect different regions of air-sea interaction in the world ocean. They are not confined to single ocean basins, but may extend over very long distances before the water is re-injected into the surface mixed layer. Through the connecting pathways in the ocean, air-sea interaction in one region can affect climate in another region. Analysing the oceanic pathways gives insight in the transports that play a critical role in the climate system and determine the stability of the present climate.

A complication is that water-mass properties do slowly change in the interior, because water-masses are mixed by small-scale processes. Still, one may trace water-mass parcels, but the properties of, for instance, North Atlantic Deep Water (NADW) gradually change while it is advected southward. The mixing rate of the water-mass is determined by two-dimensional turbulent advection and does not depend on the details of small-scale diffusion.

The thermohaline circulation (THC) is the large-scale circulation of the ocean driven by fluxes of heat and freshwater at the surface. The THC affects climate at decade-to-century timescales. The conveyor-belt hypothesis \(^1\) provides a useful concept for this circulation. Surface water cools and sinks in the northern North Atlantic, becomes NADW, and spreads southward into the deep ocean. It is replaced by warm surface water from the south that makes the European climate relatively warm. At various locations, upwelling connects the deep flow of NADW to a return flow of warm surface water, which closes the conveyor-belt (Figure 1). Due to the lack of measured data, the structure of the conveyor-belt cannot be determined directly from observations, but it can be investigated in a comprehensive ocean general circulation model (OGCM) by
tracking water parcels. In this highlight, we explore the pathways of the water-masses that constitute the return flow for the sinking NADW. A new, additional route is suggested by these calculations. By tracing the surface origin of the water-masses that are transported along this route, we determine where air-sea interactions set the properties of the water that flows to NADW formation sites.

In another application of the parcel tracking method, we investigate the surface origin of the water-masses that constitute the Equatorial Undercurrent (EUC) in the Atlantic and the associated sub-tropical cells, which are wind-driven features of the ocean.

**Method**

**Trajectories** • In fluid mechanics, ‘fluid particles’ are infinitesimal small compared to the dimensions of the system under consideration, but large compared to distances between molecules. In an analytical description, every point has a unique velocity at a given time, so one can change from Eulerian to Lagrangian variables, and trajectories are well defined. In a discrete description, this is less straightforward, but it is still possible to define trajectories. Following a water parcel along a trajectory, its properties like temperature and chemical composition may change. Trajectories that start close to each other within a grid box often diverge substantially after some time. Trajectories calculated

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*Figure 1. Schematic illustration of the conveyor-belt of the large-scale thermohaline circulation (THC). This picture, which was published a few years ago, shows the cold route from Drake Passage and the warm route from Indonesia for the surface flow into the South Atlantic, but not the Tasman leakage route south of Australia discovered by KNMI and its partners in the TRACMASS project. Source: IPCC Synthesis Report 2001.*
Recent highlights from model output depend on the grid size and the way sub-grid processes are parameterised in the model, just as the underlying model velocities do. Here our goal is to resolve the relevant two-dimensional turbulence. To this end, trajectories of parcels are calculated from the output of an eddy-permitting ocean general circulation model.

**Implementation** • Until recently, studies that employ parcel tracking were often qualitative \(^3\). This highlight presents results from the European project TRACMASS (Tracing the water-masses of the Atlantic and Mediterranean) in which two innovations were combined regarding parcel tracking in numerical model data. The first innovation was to set the number of the parcels that are released proportional to the mass transport across the initial section \(^3\), each trajectory carrying the same mass transport. The second innovation was to use an analytical solution instead of a numerical procedure for solving the differential equations from which a trajectory is calculated \(^4\). This gave rise to a fast and efficient algorithm and enabled the calculation of millions of trajectories \(^5\). The resolution of the individual trajectories is implied by the resolution of the ocean model. How well the flow of the transport distribution is resolved also depends on the number of parcels.

We report on Lagrangian calculations based on the last 3 year from a longer run of the OCCAM global, eddy-permitting ocean model \(^6\). OCCAM has 36 z-levels in the vertical and a uniform horizontal resolution of \(1/4^\circ\) by \(1/4^\circ\). Since in OCCAM the Boussinesq approximation is made and volume rather than mass is conserved, each trajectory carried the same volume transport. Resolving the full time dependence that is contained within all archived data is impossible because of computational limitations. For this reason, seasonally averaged fields were used for the trajectory calculations. Advecting parcels with time-averaged Eulerian velocity fields of the OCCAM model, however, leads to serious biases \(^7\). Biases are much smaller in isopycnal (equal density) coordinates, because motion in the ocean tends to follow isopycnal rather than horizontal surfaces. Isopycnal transports are the product of a velocity and a layer thickness. We calculated the mean isopycnal transports for each season from archived 5-day mean OCCAM velocity fields interpolated on isopycnal coordinates. Next, the transports were converted back to velocities in z-coordinates using the averaged layer thicknesses. These velocities have been used for the trajectory calculations.

**Results**

**Tasman leakage** • The technical innovations discussed above greatly improved the efficiency and accuracy of trajectory calculations. This led to new scientific results. One example is the discovery of a new, additional route for the ocean conveyor-belt. Over the last years, studies have focussed on the question which of two routes for the return flow of the THC into the South Atlantic is more important. The cold route commences at Drake Passage. Part of the cold water from Drake Passage is heated before it crosses the equator. In
the warm route, water goes through the Indonesian Throughflow between the Indonesian isles from the Pacific into the Indian Ocean, and next into the Atlantic Ocean by intermittent heat and salt advection by Agulhas rings. The dominance of one route above the other has immediate consequences for climate and climate stability. If the cold route dominates, the conveyor-belt is susceptible to atmospheric forcing in the Southern Hemisphere. If the warm route dominates, the conveyor-belt depends on the intermittent shedding of Agulhas eddies south of Cape Town.

The tracking technique described above provides an accurate picture of all pathways that go into the return flow of the conveyor-belt. To this end, the trajectories of parcels that belong to the northward flowing branch of the THC at a section across the equatorial Atlantic are computed backwards in time. Each trajectory is stopped when it reaches one of the four borders of the Indo-Atlantic basin, the Drake and Indonesian passages, a section linking Australia to Antarctica, and the equatorial Atlantic.

We obtain both classical paths: the cold and warm route. However, the routes are much intertwined. Nearly all the water of the cold route recirculates in the Indian Ocean before it returns to the Atlantic (Figure 2). Examining individual trajectories (not shown) makes clear that both the water from the warm route and the water from the cold route recirculates. As a consequence, not only the warm route, but also the cold route is influenced by the shedding of Agulhas eddies. At the Atlantic equator, their water-masses are completely mixed and have become indistinguishable. The striking new feature that appears is a pathway linking the westward flowing Tasman Current to the northward flow across the equatorial Atlantic, with Agulhas leakage being crucial (Figure 2). This ‘Tasman leakage’ contributes about 20% of the upper branch of the THC. KNMI and two of its TRACMASS partners have found the new Tasman route in three ocean models. The magnitude and characteristics are similar in the three models, and are supported by a new analysis of the WOCE observational database 8).

Next, we trace the origin of the water coming from the Tasman outflow. Starting at the border along the line that links Australia to Antarctica, trajectories from all parcels constituting the Tasman leakage are computed further backwards until they hit the surface mixed layer. In this way the surface origin of all parcels that represent the Tasman outflow is determined. We find that they essentially originate from the Subantarctic zone as Subantarctic Mode Water (SAMW), see Figure 3. These waters are then transported within the Antarctic Circumpolar Current, where they are partially modified to Antarctic
Figure 2. Lagrangian horizontal streamfunction of the vertically-integrated transport of the upper branch of the THC between Indo-Atlantic and the Atlantic equator. The contour interval is $10^6$ m$^3$s$^{-1}$. Water coming from Tasmania is depicted with a dark blue arrow, from Drake Passage with a light blue arrow, and from the Indonesian Throughflow with a red arrow.

Figure 3. Downward velocity ($10^{-6}$ m$^3$s$^{-1}$) through the base of the surface mixed layer of water that eventually ends in the Tasman leakage. The integral over the field equals the total Tasman leakage of $3.2 \times 10^6$ m$^3$s$^{-1}$. The field was obtained by backtracking $3 \times 10^5$ Tasman leakage particles.
Intermediate Water (AAIW). Eventually they loop back westwards and connect with the Tasman Current.

South of Australia, Tasman water has characteristics in between those of the cold and warm route, except for salinity, which is the highest for the three routes. Note that in all three cases the salinity is very low and the waters are fresh. The water from the Tasman outflow, the Indonesian Throughflow, and most of the water from Drake Passage comes together near Cape Agulhas. The water in the cold and warm routes flows mainly near the surface and is strongly influenced by atmospheric forcing. It is subject to strong evaporation and the water from the cold route is strongly heated as well. The Tasman waters flow deeper and are much less exposed to air-sea interaction. It is the only route for which most of the water never reaches the mixed layer. It thus becomes the most dense, cold and fresh of the three.

Sources of the EUC • At the Atlantic equator the warm return flow in the conveyor-belt is concentrated along the western boundary in the North Brazil Current (NBC). At 5°N, most of the NBC curves back into the eastward flowing EUC, while the remaining part of the NBC continues northward along the west coast. The main branch of the conveyor-belt follows the EUC. This is a strong current, about 100 m below the sea surface, which is connected with westward flowing surface currents to its north and south. The conveyor-belt follows the northern route and connects to the Gulf Stream in the Caribbean. The NBC and EUC transport more water than is contained in the conveyor-belt. Apart from the large-scale overturning associated with the conveyor-belt, there exist more shallow and regionally confined wind-driven overturning cells. Wind-driven divergent flow forces upwelling all along the equator. The poleward surface flow outside the western boundary currents and the equatorward subsurface flow to the upwelling region form subtropical cells. In the South Atlantic, there is a complicated interplay between the conveyor-belt and the subtropical cell.

The water that recirculates in the subtropical cells subducts some 20 degrees off the equator. In the South Atlantic, the subsurface equatorward flow reinforces the conveyor-belt. In the North Atlantic the subtropical cell opposes the conveyor-belt, and is almost absent. The subduction sites where the poleward surface flow is connected to the subsurface equatorward flow are the off-equatorial regions where air-sea interaction determines the properties of the EUC, as mixing in the interior of the ocean is small. These are also the regions where extratropical air-sea interaction influences tropical climate variability. We traced the sources of the Atlantic EUC by computing trajectories backward in time until they hit the surface mixed layer 9. Figure 4 shows that the subtropical South Atlantic is indeed the main source for the EUC. The subducted water-masses follow a pathway that is mainly within the NBC. Less than a tenth of the transport in the EUC has a Northern Hemisphere origin. The subduction region that ventilates the EUC from the north is found along the North Equatorial Current. Thereafter, parcels follow an interior pathway
Recent highlights

The wind-driven subtropical cells and the THC in the South Atlantic are closely connected. A large part of the conveyor-belt follows the EUC, and the subduction region for the EUC is almost completely within the South Atlantic. This implies that in the South Atlantic the poleward surface flow of the subtropical cell and the equatorward warm surface flow of the conveyor-belt meet in a zone of confluence in the subtropics where they subduct and flow equatorward in the NBC. While most of the water from the cold and warm route of the THC enters the South Atlantic near the surface, the Tasman leakage part remains deeper and probably does not enter the EUC.
Conclusions

We can describe and quantify the spread and transformation of water masses with a parcel tracking method. A new, additional route was found for the surface return flow of the conveyor-belt that originates south of Australia. Water-masses of the cold route from Drake Passage and the warm route from Indonesia thoroughly mix before entering the Atlantic Ocean. Pathways that connect remote sites of air-sea interaction were calculated, in particular in the subtropics and the tropical Atlantic. The EUC in the Atlantic Ocean mainly originates from the south because the meridional overturning cells associated with the EUC are strongly affected by the THC.