Observed Interhemispheric Meridional Heat Transports and the Role of the Indonesian Throughflow in the Pacific Ocean

KEVIN E. TRENBERTH^a AND YONGXIN ZHANG

National Center for Atmospheric Research, Boulder, Colorado

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ABSTRACT

The net surface energy flux is computed as a residual of the energy budget using top-of-atmosphere radiation combined with the divergence of the column-integrated atmospheric energy transports, and then used with the vertically integrated ocean heat content tendencies to compute the ocean meridional heat transports (MHTs). The mean annual cycles and 12-month running mean MHTs as a function of latitude are presented for 2000–16. Effects of the Indonesian Throughflow (ITF), associated with a net volume flow around Australia accompanied by a heat transport, are fully included. Because the ITF-related flow necessitates a return current northward in the Tasman Sea that relaxes during El Niño, the reduced ITF during El Niño may contribute to warming in the south Tasman Sea by allowing the East Australian Current to push farther south even as it gains volume from the tropical waters not flowing through the ITF. Although evident in 2015/16, when a major marine heat wave occurred, these effects can be overwhelmed by changes in the atmospheric circulation. Large interannual MHT variability in the Pacific is 4 times that of the Atlantic. Strong relationships reveal influences from the southern subtropics on ENSO for this period. At the equator, northward ocean MHT arises mainly in the Atlantic (0.75 PW), offset by the Pacific (−0.33 PW) and Indian Oceans (−0.20 PW) while the atmosphere transports energy southward (−0.35 PW). The net equatorial MHT southward (−0.18 PW) is enhanced by −0.1 PW that contributes to the greater warming of the southern (vs northern) oceans.

1. Introduction

The sun–Earth geometry guarantees an excess of radiant heat received in the tropics and a deficit at high latitudes that are compensated by poleward meridional heat transports (MHTs) by the atmosphere and ocean. Atmospheric transports are reasonably well determined from atmospheric reanalyses, but ocean transports as a function of space and time have been difficult to determine reliably, although mean values have been available for some time (Trenberth and Caron 2001; Trenberth et al. 2019). Here, we attempt to remedy this situation.

The oceans play a major role in the climate system as the main memory of any energy imbalance. The ocean

currents and eddies further redistribute the energy, mainly in the form of heat, both vertically and horizontally. Using closure of the energy budget, we can deduce the net surface energy fluxes as a residual of top-of-atmosphere (TOA) measurements and the vertically integrated atmospheric energy divergence (Trenberth and Solomon 1994; Trenberth 1997; Trenberth and Fasullo 2017, 2018).

The ocean transports heat from where there is a net flux of energy into the ocean to where there is a net flux out. The surface heat fluxes have then been combined with estimates of the vertically integrated ocean heat content (OHC) (Cheng et al. 2017; Zuo et al. 2018) tendency to produce estimates of the ocean heat divergence (Trenberth et al. 2019). These were then in turn integrated from the north southward to compute ocean MHTs. In particular, we computed zonal mean global, Indo-Pacific, and Atlantic basin ocean MHTs as 12-month running mean time series and for the mean annual cycle for 2000 to 2016 as a function of latitude for the first time.

In Trenberth et al. (2019) zonal mean MHTs were produced for the Arctic and Atlantic Oceans combined, the

^a Denotes content that is immediately available upon publication as open access.

^a ORCID: 0000-0002-1445-1000.

Corresponding author: Kevin E. Trenberth, trenbert@ucar.edu

Indo-Pacific Ocean, and the global oceans. Accordingly, the large heat losses over the Arctic Ocean are replenished by northward ocean heat transports in the Atlantic. The melting and thawing of sea ice were approximately accounted for. Not properly dealt with were the changes in runoff from land, although the 12-month running mean removes most of those effects.

For the Pacific, we integrated southward from the Bering Strait, where through transports are small enough to be neglected, but could be considered. However, the Indian and Pacific Oceans were combined because of their connection through the Indonesian region, called the Indonesian Throughflow (ITF). In [Trenberth et al. \(2019\)](#), a preliminary exploration of MHT relationships with El Niño–Southern Oscillation (ENSO) revealed some new relationships, but these are likely better understood if we consider the MHT in the Pacific and Indian Oceans separately, which is a key purpose of this paper.

Hence, in this paper, we explicitly take the ITF into account and therefore separate the MHT from the two oceans. This is nontrivial, because there is a net volume flow from the Pacific westward and southward into the Indian Ocean on average and it is accompanied by a significant transport of heat. It also varies considerably with ENSO, as discussed below. As heat moves southward in the Indian Ocean, the ocean waters have to return to their starting point. Accordingly, there is a continual flow of ocean waters around Australia ([Godfrey 1996](#)). Because the ocean is not very deep between Tasmania and the mainland, most of that return flow is eastward south of Tasmania, and then it flows northward in the Tasman Sea or possibly farther east. Therefore, neither the energy budget nor that mass budget is closed for each ocean alone, and the amount of heat transported depends upon the reference value.

[Godfrey \(1996\)](#) provided a nice summary of the state of knowledge of the ITF based upon fragmentary data and highlighted the role of the warm volume transport between the various Indonesian islands that amounted to a net heat transport, updated by [Sprintall et al. \(2014\)](#) and [Gordon et al. \(2019\)](#). The actual heat transport is now often stated relative to some baseline value such as a temperature of 0°C, but is really a temperature transport rather than a heat transport because it also involves a net mass transport. [Godfrey \(1996\)](#) pointed out that the ITF flow of the Pacific waters into the Indian Ocean was countered by an eventual eastward flow south of Tasmania at temperatures some 10°C or so lower and “a mean throughflow of 10 Sv would therefore export about 0.5 PW” (p. 12 228) from the Pacific to the Indian Ocean and southward ($1 \text{ Sv} = 10^6 \text{ m}^3 \text{ s}^{-1}$).

The ITF has now been monitored off and on since November 1996 and over 13 years of recorded data exist, greatly expanding on the earlier expendable bathythermograph-based analyses of [Wijffels and Meyers \(2004\)](#) and [Liu et al. \(2015\)](#). The primary inflow path of Pacific water into the Indonesian seas is the Makassar Strait, channeling 12.5 Sv, about 77% of the total ITF ([Gordon et al. 2019](#)). The Makassar Strait annual cycle transport ranges from about 7 to 16 Sv. Strong southward transport occurs during boreal summer, with weaker (stronger) southward flow and a deeper (shallower) subsurface velocity maximum during El Niño (La Niña). The southward heat flux relative to 0°C ranges from −0.60 PW in 2015 to −0.98 PW in 2010, averaging −0.83 PW for 2004 to 2016 (excluding 2012) (A. Gordon, personal communication, March 2019). In terms of variability, [Gruenberg and Gordon \(2018\)](#) reported that the southward Makassar Strait heat flux anomaly (relative to 2004–17) peaked at 0.13 PW during 2008 and 2009, then decreased to −0.25 PW (less southward) minimum during 2015 with the vertical structure of the transport accounting for 78% of the variance, whereas changes in the temperature profile account for 28%. Accordingly, most of the heat transport is associated with the volume transport.

Variability in ITF has been extensively analyzed by [Wijffels and Meyers \(2004\)](#) and [Liu et al. \(2015\)](#), who note that while ENSO is a primary contributor to the fluctuations, the Indian Ocean dipole (IOD) also plays an important role, as IOD-induced coastal Kelvin waves propagate along the Sumatra–Java coast of Indonesia and influence ITF transport. ENSO depends on the rearrangement of heat within the climate system and especially in the tropical Pacific Ocean ([Mayer et al. 2014](#); [Cheng et al. 2019b](#)). There is a build-up (recharge) of heat in the warm pool area of the tropical western Pacific in the vicinity of Indonesia prior to an El Niño event, and then movement of heat laterally and major adjustments in the vertical distribution of heat and the thermocline during the course of the event as the trade winds relax and the Bjerknes feedback processes kick in. The atmosphere plays a vital role as a bridge among the oceans and to the extratropics through changes in the atmospheric circulation and associated surface fluxes, resulting in a significant diabatic component, as heat is ultimately radiated to space and lost, resulting in a discharge of energy ([Cheng et al. 2019b](#)). The links between the Pacific and Indian Oceans occur not only through the atmosphere but also through changes in volume flow and heat transport through the Indonesian region ([Wijffels and Meyers 2004](#); [Sprintall et al. 2014](#)). A key purpose of this paper is to throw further light on especially the separate roles of the Indian and Pacific Oceans, which are linked in the tropics via the ITF.

In particular, [Oliver et al. \(2017\)](#) noted the pronounced and unprecedented ocean heat wave over the southern Tasman Sea in late 2015 to 2016, and linked it to changes in the East Australian Current. The latter is a western boundary current in the subtropical Pacific just off the east coast of Australia from the tropics to about 35°S but that spins off warm pool eddies farther south. [Oliver et al. \(2018\)](#) explored such ocean heat waves more generally and further noted the links to the East Australian Current. Tasman Sea marine heat waves were found to be a response to ocean heat transport from lower latitudes that sets up above normal OHC ([Behrens et al. 2019](#)), based on a coarse-resolution global ocean model.

While it is well established that most variations in the area do occur with El Niño [discussed quite extensively in [Oliver et al. \(2017\)](#)], most of these are thought to be associated with changes in the atmospheric circulation, as higher pressure prevails over Australia in El Niño events and southwesterlies often prevail over New Zealand downstream. Hence the change in local winds also force some modifications in surface fluxes and wind stress. Any link between ENSO-related variations in the ITF and the Tasman Sea heat waves has been generally assigned to the atmospheric bridge connections. The studies thus far have overlooked the likelihood that there is also a direct ocean connection through the changes in mass and heat transport with the ITF that indeed relate to opposite changes in the East Australian Current region arising through mass continuity. Here we partly explore this possibility in the larger global context of the ocean heat transports.

The links between the ITF and ENSO have been known for some time but were explored in more detail by [Mayer et al. \(2018\)](#), using output from the ocean data assimilation from ECMWF's Ocean Reanalysis System 4 (ORAS4) and ORAS5. ORAS5 has a much higher resolution (1/4° horizontal resolution and 75 vertical levels). Their time series are more complete than those of the direct observations but limited by how well the model depicts the complexity of the bottom and island topography in the Indonesian region, and their volume and heat transports appear to be slightly high. The observed values are best established by the INSTANT (International Nusantara Stratification and Transport) program ([Gordon et al. 2010](#)). The ORAS5 volume transports averaged 18.6 Sv versus the observed estimates ranging from 11 to 19 Sv and averaging 15 Sv. Unprecedented reduction of ITF volume and heat transport played a key role in the anomalous 2015/16 El Niño event ([Mayer et al. 2018](#)), which adds to the information given by [Oliver et al. \(2017\)](#). [Mayer et al. \(2014\)](#) and [Cheng et al. \(2019b\)](#) further explored the energy budgets of ENSO and the role of transports

among oceans, either via atmospheric bridges or the ITF, as well as the changes with depth.

Given our new energy budgets, we are also in a position to reexamine the interhemispheric energy transports in detail. The annual cycle of energy transport across the equator was first documented by [Trenberth and Stepaniak \(2003a,b\)](#) and [Fasullo and Trenberth \(2008\)](#) but with the annual mean close enough to zero to be within the uncertainty of those earlier data analyses. Those studies focused on the atmosphere and the role of the Hadley circulation, but identified the important local role of ocean transports driven in part by evaporative cooling. The annual cycle of energy transport on the equator is large and the seasonal cycle of the location of the intertropical convergence zone (ITCZ) is highly negatively correlated with the atmospheric heat transport at the equator and highly positively correlated with the interhemispheric contrast of tropical SST in both observations and coupled climate models ([Donohoe et al. 2014](#)).

A number of idealized modeling studies have noted that the overall southward cross-equatorial heat transport by the atmosphere requires the location of the ITCZ in the Northern Hemisphere in the annual mean while the ocean heat transport is in the other direction, altering the energy flux equator (where the meridional energy flux goes to zero) ([Kang et al. 2008](#); [Donohoe et al. 2014](#); [Frierson and Hwang 2012](#); [Frierson et al. 2013](#); [Bischoff and Schneider 2014](#)). [Irving et al. \(2019\)](#), based upon model results, suggest that because the main aerosols are in the Northern Hemisphere, the main excess heat uptake is in the Southern Hemisphere oceans, and this results in a net northward heat transport by the oceans across the equator. However, the models typically do not replicate clouds adequately and the Southern Ocean radiative imbalance in models, in particular, is not correct (e.g., [Trenberth and Fasullo 2010](#); [Haynes et al. 2011](#); [Bodas-Salcedo et al. 2014](#)). Accordingly, while the northern oceans are indeed warming at a slower rate, as we also show here, there is not a net transport of heat into the Northern Hemisphere when the atmosphere is also considered.

Some model-based syntheses of ocean heat transports are becoming available but depend on the veracity of the model and how well it is in balance. For instance, [Forget and Ferreira \(2019\)](#) produced ocean heat transport estimates and a very useful discussion of the total versus the divergent component from a model and its adjoint, based on the ECCO (Estimating the Circulation and Climate of the Ocean; <https://ecco.jpl.nasa.gov/>) version 4 system, employing a method that jointly adjusts estimates of surface fluxes and the model's state estimation. This method contains assumptions and adjustments that make the results questionable; for instance, their

estimate of peak northward MHT in the Atlantic is only 0.7 PW in spite of strong observational evidence to the contrary in moored arrays (see Trenberth and Fasullo 2017), and also the values through Bering Strait are orders of magnitude too large.

In this paper, we build on the results from Trenberth et al. (2019) by incorporating estimates of the ITF heat transports in order to split the MHT estimates into two parts associated with each of the Indian and Pacific Oceans. We then further explore the links with ENSO and comment on the role of ENSO and the ITF in the Tasman Sea variations. Finally, we document the details of the MHT across the equator and provide a more complete accounting of the interhemispheric energy transports, along with their variability—which is substantial.

2. Methods and datasets

We use monthly TOA Clouds and the Earth's Radiant Energy System (CERES) Energy Balanced and Filled (EBAF) Edition 4.0 radiation on $1^\circ \times 1^\circ$ grids, from Langley Atmospheric Science Data Center (http://ceres.larc.nasa.gov/order_data.php) (Loeb et al. 2009). Observations from CERES begin in March 2000 and have been extended back in time (Allan et al. 2014) using model results and other constraints, so that we use results from January 2000 on.

The atmospheric computations here all utilize only the European Centre for Medium-Range Weather Forecasts (ECMWF) interim reanalysis (ERA-Interim, hereinafter ERA-I; Dee et al. 2011) (<https://www.ecmwf.int/en/forecasts/datasets/reanalysis-datasets/era-interim>). Improvements in the methodology for computing vertically integrated energy divergence include adjustments for the inevitable spurious mass imbalance and allowance for the enthalpy associated with precipitation (Trenberth and Fasullo 2018). When the vertically integrated atmospheric energy divergence is combined with R_T , the TOA net energy flux downward, the net surface energy fluxes upward, F_s , are computed as a residual. Uncertainties become large as the spatial and temporal scales are reduced, but with recently available data from satellites and atmospheric reanalyses, the net flux is reasonably well known to be better than 10 W m^{-2} on scales of over 1000 km for annual means (Trenberth and Fasullo 2017, 2018). Trenberth and Fasullo (2018) presents results for 2000 to 2016.

As documented in Trenberth et al. (2019), we mainly use ocean reanalyses from ECMWF ORAS5 (Zuo et al. 2018), but anchored for the ITF by the direct ocean observations of Gordon et al. (2019). ORAS5 is an eddy-permitting ocean reanalysis with a prognostic thermodynamic-dynamic sea ice model that assimilates multivariate fields, including sea surface height from

altimetry, sea ice concentration data, and surface forcing from ERA-I. It was produced using the V3.4.1 of the NEMO (Nucleus for European Modeling of the Ocean) ocean model at a resolution of 0.25° in the horizontal and 75 nonuniformly spaced levels in the vertical (Zuo et al. 2018; Mayer et al. 2018). For ORAS5, five ensemble members are generated by perturbing both observations and forcing fields to reflect the main uncertainty. Because the computation of OHC tendency inflates the noise (it is effectively a high-pass filter), we first take centered differences (thereby keeping the tendency centered on the time of interest), and smooth the result with a 1/12 [1–3–4–3–1] filter that removes fluctuations shorter than 4 months.

Given the net surface flux of energy locally, the estimates are combined with estimates of changes in OHC to compute the vertical integral of the divergence of the ocean heat transport, which thereby allows for an estimate of the ocean movement of heat (Trenberth et al. 2019). In particular, the focus is on the zonal integral $\int$ of ocean variables (over longitude), which includes an $a \cos \phi$ factor, where a is Earth's radius. We compute these by integrating from the North Pole southward to give the zonal mean MHT at latitude ϕ :

$$\text{MHT}(\phi) = \int_{\phi}^{90^\circ} [F_s + d\text{OHC}/dt] a d\phi. \quad (1)$$

All datasets were averaged or interpolated to a 1° resolution for the computations presented.

By integrating from the north, the Arctic and Atlantic are included together. The net northward heat flux by the ocean through the Bering Strait varies from year to year (Woodgate et al. 2012) but is very small compared with the zonal means, and is neglected (Trenberth et al. 2019). In the Pacific the integration begins at the Bering Strait, and in the Indian Ocean it begins at the southern extent of the Asian continent. South of 35°S (Africa), the ocean contributions are combined into a “Southern Ocean” MHT. Hence, the accumulated inferred values at Antarctica give the error. The errors primarily stem from the OHC mismatch with the CERES and F_s values. Haines et al. (2012) note that ERA-I surface fluxes are biased by order 5 W m^{-2} globally and the ability of an analysis to correct that bias depends on the ocean observations. For the Argo era, implied imbalances produce a spurious MHT ranging from about 0 to -0.5 PW ; 0.3 PW globally is equivalent to about 0.8 W m^{-2} imbalance over the global ocean. Estimates were greatly improved by constraining the MHT to be zero at the northern and southern extents of the ocean basin on an annual basis, enabling biases between the TOA and OHC data to be reconciled (Trenberth et al. 2019). This

actually cleans up results from different OHC datasets by effectively bias correcting them. Indeed, the individual ensemble members from ORAS5 exhibit a spread of about 0.4 PW and the cleanup procedure is beneficial in greatly narrowing the spread (Trenberth et al. 2019).

The above process results in a set of values for the Arctic-Atlantic and the Indo-Pacific. The latter are joined through the ITF. Given that we have used ORAS5 OHC values, we have also adopted the ORAS5 ITF heat transports from Mayer et al. (2018) to complement the MHT computed using our integrations from the north of the surface heat fluxes and OHC changes. The ITF heat transport is westward and southward, and hence is introduced as a reduction in the southward Pacific heat transport, and added to the southward Indian Ocean heat transport centered at 9°S but tapered off over several latitudes ranging from 7° to 11°S.

Although the resolution of ORAS5 is 0.25° it is difficult to depict the bottom topography and complexity of the many routes through the Indonesian islands. It is not surprising that the mean volume and heat transport are somewhat larger than the implied observed estimates of Gordon et al. (2019) although the latter are incomplete. The most complete observational estimates were for a limited period during INSTANT when the Makassar Strait component was found to be 77% of the total southward heat flux through the ITF. If this is extended to the whole observed period from 2004 to 2017 then the mean heat transport of -0.833 PW implies -1.08 PW for the ITF as a whole. We use this value in place of the computed -1.34 PW from ORAS5 for the mean but we otherwise use the ORAS5 ITF anomalies unchanged.

3. Results

a. Meridional heat transports

The annual mean ocean MHT is determined largely by the TOA radiation and the atmospheric MHT (Fig. 1), as in Trenberth et al. (2019). The ocean partitioning among the three main oceans utilizes the net surface flux over each ocean in combination with the tendency in OHC to compute the MHT as a residual. The OHC tendency then accounts for the trends associated with climate change, but must be consistent with the TOA radiation trend. For the mean, the adjustments to reconcile the two datasets are small. As given above, the MHT is integrated from the north southward and we have inserted an ITF contribution of -1.08 PW into the raw Indian Ocean MHT and subtracted that from the raw Pacific Ocean MHT with a small merging zone. The departures from the overall mean are fully included in the ITF along with its annual cycle. Note that these are

FIG. 1. Annual mean meridional heat transports (PW) for 2000 to 2016 for the total ocean (blue) and the Atlantic (purple), Pacific (red), and Indian Oceans (green), as defined in the map below. The dashed lines show values for each ocean as part of the combined southern ocean MHTs, south of Africa. The ITF is included.

not really energy transports as the mass budget is not closed except for the global ocean.

The configuration and main elements controlling what happens locally are illustrated (Fig. 2). Of particular note is the bottom bathymetry of the ocean. The shallow straits around many of the Indonesian islands do not transport much volume. The flow from the ITF may partially head southward into the Leeuwin Current, which hugs the west Australian coast and turns eastward south of Australia. Some may extend farther west to the coastal waters of Africa (Godfrey 1996). Any eastward flow in the Leeuwin Current and its extension is disrupted by Tasmania and the relatively shallow Bass Strait (average depth about 60 m). Hence it more likely becomes linked to the broader Antarctic Circumpolar Current at its northern edge and flows into the southern Tasman Sea, where New Zealand and the Campbell Plateau form a significant obstacle that diverts some of the flow northward in the eastern half of the Tasman Sea. Much of the Antarctic Circumpolar Current is

FIG. 2. The primary region where the mass flows in the ITF have impacts. The shades of gray show the bathymetry at the surface (black) and at 500-, 1000-, and 1500-m depth. The background field is the annual mean SST (scale at bottom). The arrows depict various currents, the cyan arrows show warm waters in the ITF, East Australian Current, or Leeuwin Current. The dark blue currents show the Antarctic Circumpolar Current and the associated west-wind drift, plus the West Australian Current. The Tasman Sea lies between Australia and New Zealand.

steered farther south around the Campbell Plateau. Consequently, any eastward current south of Australia may also be steered into the south Tasman Sea and then around to the north of New Zealand. Farther north, the East Australian Current is diverted eastward to the north of New Zealand, north of 33°S as part of a quite strong eastward current, clearly evident in the surface drifter-inferred currents (Lumpkin and Johnson 2013). The East Australian Current spins off warm core eddies into the Tasman Sea.

If we simply ignore the ITF and divide the Pacific and Indian Oceans, as in the lower part of Fig. 1, then the MHT time series that results (Fig. 3) shows the southward heat transport in both the Pacific and Indian Oceans. However, once the ITF contributions are included, the result (Fig. 4) shows the greatly enhanced southward MHT in the Indian Ocean while the South Pacific features northward heat transport from 45° to 10°S. In fact, it looks odd with the narrow band of southward transport from the equator to 10°S but this energy effectively flows into the Indian Ocean.

The lack of a mass balance in both oceans means that the transports depend critically on the definition of heat or energy, and the reference value, taken as 0°C, has resulted in the choice of 1.08 PW associated with 15-Sv

FIG. 3. Time series as 12-month running means of the MHT without the ITF included for the (top) Pacific and (bottom) Indian Ocean in PW.

volume transport; if 10°C were used instead, the redistribution values would be about 0.61 PW less. This arbitrariness vanishes when anomalies are considered.

The mean annual cycle (Fig. 5) has considerable character. Southward heat transports dominate the southern winter from May to October from the land north of the equator, while pronounced northward

FIG. 4. Time series as 12-month running means of the MHT with the ITF included for the (top) Pacific and (bottom) Indian Ocean in PW.

FIG. 5. Inferred mean annual cycle of the MHT with the ITF included for the (top) Pacific and (bottom) Indian Ocean in PW.

FIG. 6. Time series as 12-month running means of the MHT anomalies with the ITF included for the (top) Pacific and (bottom) Indian Ocean in PW.

transport of energy occurs in the southern summer, from December to March north of 10°S , when maximum solar heating is south of the equator. In the Pacific, the lowest northward heat transport at 30°N is September–October when northern SSTs are highest, and the strongest northward MHT is at 5°N in the southern summer. Indeed, the largest annual cycle of MHT of 8 PW range occurs at 8°N , about the mean location of the ITCZ. At that latitude, the maximum southward transport is in September while a broad northward maximum occurs from January to March. The northward MHT maxima in the Southern Hemisphere subtropics, where the ITF effects are prominent, are in midwinter and midsummer, when the monsoons are strongest, and less in the transition seasons. In the Indian Ocean, the annual cycle of MHT undergoes variations closer to a 12-month cycle, northward on the equator in northern winter and southward in southern winter.

The MHT anomalies (Fig. 6) are much stronger in the Pacific than the Indian Ocean (Fig. 7) and the main fluctuations are associated with ENSO (Fig. 8). In the Southern Hemisphere, the two anomalies are more comparable in magnitude; it is mainly near the equator, and peaking about 5°N , that the Pacific MHT variability dominates. Moreover, the Southern Hemisphere anomalies at times reveal reverse changes in the two oceans, consistent with the role of the ITF. Exploration of the correlations with El Niño indices [oceanic Niño index (ONI)] (Fig. 8) as a function of lead and lag, shows the ONI leading MHT near the equator in the Pacific by

3 to 4 months, consistent with the ITF response (Mayer et al. 2018). Also intriguing is the strong tendency for Pacific MHT in the Southern Hemisphere from 20° to 30°S to lead ONI by 8 months, and it also leads the MHT in the Indian Ocean in the same zone by 8–9 months (not shown). At least for this period, strong northward MHT near 25°S propagates northward to influence the equatorial region in the Pacific, especially after 2005. The

FIG. 7. Standard deviation of the MHT in each ocean in PW, with ITF included.

FIG. 8. Correlation between the 12-month running mean MHT anomalies and the ONI for ± 24 months, with ONI leading for positive values. Values greater than 0.65 are marked with a white contour. The 5% statistical significance level is 0.46.

weaker relationship prior to then may well be a consequence of the absence of adequate Argo data. In the 2015–16 El Niño event, a lot of the northward MHT propagation comes from the Indian Ocean. Near 25°S, there is a strong positive correlation between ONI and MHT in the Indian Ocean, presumably in response to the reduced heat transport through the ITF.

b. Australasian relationships

In this section we briefly explore the possible consequences of the ITF and the associated flow around Australia for the Tasman Sea. As noted earlier, an unprecedented marine heat wave took place east of Tasmania in late 2015. Usually, in association with El Niño, high sea level pressure forms over Australia and results in stronger westerlies south of 40°S, south of Australia, which turn to southwesterlies across the south Tasman Sea and New Zealand (Trenberth and Caron 2000) in all seasons. These are accompanied by frequent cold fronts and cold air outbreaks, so that New Zealand has been one of the few areas where surface temperatures are cooler than normal during El Niño (Trenberth and Caron 2000). This was not the case in the 1997/98 and 2015/16 El Niño events, however. In both cases, strong anticyclones prevailed east (2015/16) or northeast (1997/98), and over New Zealand for November to March, supporting a northerly component to the anomalous prevailing wind flow. Accordingly, the atmospheric

conditions were conducive to warmer conditions in the Tasman Sea.

The large-scale atmospheric circulation with prevailing subtropical anticyclones over the oceans, westerlies in the middle to high latitudes, and easterly trade winds in the lower latitudes sets the stage for the warm pool in the tropical western Pacific and mandates the ITF from the Pacific into the Indian Ocean. Mayer et al. (2018) demonstrated the relationship between the ITF and the curl of the wind stress in the equatorial Pacific. During El Niño, the easterlies relax and the warm pool both shoals and shifts eastward somewhat, setting the stage for a large subtropical gyre in the Pacific and a stronger East Australian Current (Oliver et al. 2018; Behrens et al. 2019). In 2015/16, as detailed by Oliver et al. (2017), the East Australian Current penetrated farther south than normal and was a primary contributor to the marine heat wave east of Tasmania. Oliver et al. (2017) found that the main anomalous warming was from advection from the north but they did not perform a mass balance analysis, and were evidently unaware of the changes in the ITF. Similarly, Behrens et al. (2019) did not mention the ITF, and their coarse-resolution model would not resolve the detailed currents in that area. The mass continuity issue raises the question of how much these changes were also supported by the reduction or absence of pressure for a return flow from the ITF through the south Tasman Sea.

The time series of ONI, ITF, and SST in the south Tasman Sea (Fig. 9) provide some insights. The relationship between ONI and ITF heat transport is readily apparent and was analyzed in detail by Mayer et al. (2018). The ITF volume flow leads the ITF heat transport by a few months. Although strong anomalies developed in the ITF in both major El Niño events (1997/98 and 2015/16), the changes during 2015/16 were unprecedented. However, in the south Tasman Sea area, the SSTs, although high in 2015/16, have no correlation with the other two indices overall. The correlations between the ITF and SST anomalies more generally (Fig. 10) show the strongest pattern with SSTs leading by 3 months and corresponding to the ENSO pattern at its peak. Six months later, with the ITF leading by 3 months, the ENSO pattern is fading, but a distinct Tasman Sea pattern emerges for this period, with higher SSTs accompanying El Niño. Nevertheless, Fig. 9 makes it clear that while this may apply for 2000 to 2016, it does not hold up well when the time series is extended. Accordingly, the Tasman Sea heat wave in 2015/16 appears to be a fairly singular event whereby the ocean and atmospheric components to the ocean anomalies were acting in consort, whereas more commonly they are not, and the atmospheric effects and other influences are apt

FIG. 9. Time series of the ONI (red and light blue shading; scale at right in blue), and the five ORAS5 members for the ITF heat transports northward in PW (left scale). Also shown (purple) is the mean SST for the south Tasman Sea, 35°–45°S, 150°–165°E; scale at right in °C.

to dominate. Similarly, Behrens et al. (2019) found no relationship between the Tasman Sea heat waves and ENSO or the Pacific decadal oscillation while Sloyan and O’Kane (2015) found pronounced decadal variability in the Tasman Sea associated with the South Pacific atmospheric storm track.

It may be possible to sort this out further with carefully constructed numerical experiments using a fairly high-resolution ocean model, and redoing the experiment of Godfrey (1996) by shutting down (blocking) the ITF; however it is not just mean conditions but also El Niño states that need to be simulated well along with the perhaps somewhat chaotic aspects of the atmospheric circulation.

Interest in this problem has re-emerged in 2019 as SSTs across the south Tasman Sea have again been at record high levels, peaking in terms of anomalies in March 2019, although preliminary examinations of the ITF do not show as strong anomalies as for 2015/16. Values of the ITF were below normal in ORAS5, but confidence in those numbers is hindered by operational changes in ORAS5 (M. Mayer, personal communication, April 2019).

Hence, with regard to the ITF and the flow around Australia, to the extent that there is a component of a return current northward in the Tasman Sea that relaxes during the El Niño, then it may contribute to warming by allowing the East Australian current to push farther south even as it gains volume from the tropical waters not flowing through the ITF. But the effects can be overwhelmed by changes in the atmospheric circulation.

c. Equatorial transports

There has been considerable interest recently in the relative energy/heat budgets of the two hemispheres, and how much MHT there is across the equator (Loeb

et al. 2014, 2016; Mayer et al. 2017). This is complicated by the fact that the system is not stationary, and it is essential to properly deal with the changes in heat storage, something that has not been done elsewhere. Hence our revised and new MHT estimates provide further insights into this issue.

A summary of the results (Figs. 11 and 12) provides the time series of MHT for the individual oceans, the global ocean, the atmosphere, and the TOA CERES values. Here, we use our new estimates of MHT for the oceans, adjusted to ensure that the ocean budgets are

FIG. 10. Correlations between 12-month running mean anomalies of SST and ITF heat flux, with SST (top) leading by 3 months or (bottom) lagging by 3 months for 2000 to 2016.

FIG. 11. (top) Time series of MHT as 12-month running means across the equator for the oceans: global, Atlantic, Pacific, and Indian; and (middle) meridional energy transports at TOA and for the atmosphere in PW. (bottom) Mean values along with the standard error of the mean, and the standard deviation in PW.

closed (MHT drops to zero at 78°S when integrating from the north). The atmospheric energy budgets are comprehensive and go to zero at both poles. The TOA radiation, however, has to be adjusted for the changes in storage within the system and this has to be compatible with the OHC and other internal changes, as we have guaranteed. Figure 11 gives numerical values along with the standard deviation of the 12-month running means, and we have used the autocorrelations at lag to estimate

the degrees of freedom in each series and thus the standard error of the mean.

The ocean transports in the Pacific at the equator vary considerably and dominate the global ocean values. Of special note are the extremely large values in 2016, associated with the large El Niño event and the huge changes in the ITF noted in the previous subsection. Values range from -0.3 PW to 1.2 PW for the 12-month running mean. A range from -0.3 to 0.6 PW exists without 2016 included. Accordingly, the actual transports depend critically on the period sampled.

Also of interest in Fig. 11, and summarized in Fig. 12, is that on the equator for 2000 to 2016 the mean ocean MHT is -0.33 PW for the Pacific, -0.20 PW for the Indian Ocean, and $+0.75$ PW for the Atlantic associated with the Atlantic meridional overturning circulation (AMOC; Trenberth and Fasullo 2017), giving a net ocean MHT of 0.22 PW northward. In turn this heat is transported into the North Atlantic and into the Arctic Ocean, with a very strong annual cycle (Trenberth et al. 2019). The schematic green arrows in Fig. 12 illustrate the main movement of heat within the ocean in regions away from the equator.

However, the atmosphere has a distinct southward transport of energy of -0.35 PW and the ocean a northward transport of 0.22 PW, while overall the CERES TOA values give -0.18 PW. Accordingly, there is an extra -0.05 PW equatorial transports that represents a heat flow into the Southern Hemisphere ocean and arises because of the uneven distribution of the ocean—much more in the Southern Hemisphere—and its uptake of heat. Mayer et al. (2017) found that the larger southward energy flux by the atmosphere was mostly associated with the adjustments arising from the

FIG. 12. Schematic of the ocean heat flows across the equator for 2000 to 2016 as blue arrows, complemented by green arrows showing flows among the oceans. (right) The global ocean, atmosphere, and totals are given in PW, along with the differential change in storage (orange) in the Southern Hemisphere.

FIG. 13. Global and hemispheric contributions to OHC changes from 2000 to 2017, relative to a mean from 1993 to 2017 for the five ensemble ORAS5 members. The mean annual cycle is removed and values are 12-month running means.

proper treatment of precipitation enthalpy, as we have done here. Owing to land and edge effects within each ocean there are small influences, estimated using the ORAS5 0.25° resolution data to be up to about 0.01 PW uncertainty. Accordingly, while the global ocean energy budget is balanced by the TOA Earth's energy imbalance (EEI), this is not true locally or for each hemisphere alone. The value of 0.05 PW is equivalent to 1.1 W m^{-2} over the ocean and it is largely because of the greater area in the south that the imbalance arises. However, this may be somewhat artificially low and relate to the adjustment procedures employed.

As a cross check, Fig. 13 presents the 12-month running mean hemispheric and global OHC down to 2000 m from ORAS5 for 2000 to 2017. Focusing on 2000 to 2016, the change is 1.0 W m^{-2} globally [276.0 ZJ (zettajoules, 10^{21} joules); the range of the five ensemble members is 265 to 282 ZJ]. However, this is unconstrained, and more reliable values occur only after Argo is in place, and for 2005 to 2016 the rate of increase of global OHC is 153.8 ZJ or 0.8 W m^{-2} globally. The actual changes in OHC averaged over the two hemispheres (Fig. 13) show much greater warming of the southern oceans from ORAS5, and this is confirmed by values from Cheng et al. (2017, 2019a). Mayer et al. (2017) find an increase in OHC in the Southern Hemisphere versus Northern Hemisphere for March 2000 to February 2007 of 0.36 and 0.20 PW respectively. In Fig. 13, for the much longer 17-yr period, the Southern Hemisphere oceans warm by 165 (159 to 169) ZJ while the Northern Hemisphere oceans warm by 111 (106 to 113) ZJ from 2000 to 2016, and their difference of 54 ZJ is equivalent to 0.10 PW. This value is roughly double that we compute using our constrained flux methods, where the budgets are closed within the uncertainties of up to about $\pm 0.2 \text{ PW}$ (see the standard errors of the transports in Fig. 11). Indeed, Fig. 9 of Trenberth et al. (2019) suggests errors on the order of 0.3

FIG. 14. Interhemispheric transports in PW for the atmosphere (light blue) above land (brown) and ocean (blue), and at the TOA. At the TOA (yellow arrows) the imbalance reflects the larger component into the Southern Hemisphere ocean (red bubble). The net anomalous surface energy fluxes for the oceans are also given. The global mean EEI does not affect transports but its regional differences do.

PW globally in ORAS5. Nevertheless, the Southern Ocean acts as a giant sponge for heat, mixing it deep within the ocean (Cheng et al. 2017).

The overall values (Fig. 14) feature TOA values that are part of the EEI value of 0.4 PW, while the transports necessarily have to balance. Note that in Fig. 14 the TOA transport value is the sum of the atmosphere and ocean transports but with an extra 0.5 PW imbalance into the southern oceans included. These equatorial energy transport values (Fig. 14) differ considerably from those of Loeb et al. (2016), who found a radiative gain in the Southern Hemisphere while a net loss in the Northern Hemisphere was associated with higher outgoing longwave radiation, in spite of the biggest signal arising from loss of Arctic sea ice and increased absorbed solar radiation. Loeb et al. (2016) and Stephens et al. (2016) found a net northward transport of energy across the equator, in part because of the different period used (the large perturbations in 2016 that were not in their analyses) and the failure to account for the differential uptake in heat in the OHC in the two hemispheres. Significant differences also arise from the revised atmospheric energy budget computations (Mayer et al. 2017; Trenberth and Fasullo 2018) and the different ocean datasets used, because several ocean analyses have been shown to be quite deficient as they do not conserve energy (Trenberth et al. 2016; Mayer et al. 2017). The results highlight the need to fully take account of the variability.

Another point of considerable interest is the fairly obvious correlations among several of the time series (Fig. 11). The MHT values for the global, Pacific, and

Indian Oceans vary somewhat in synch, as does the TOA MHT. At zero lag, the 12-month running mean global MHT has a correlation of 0.97 with the large Pacific variations, 0.38 with the Indian Ocean, and 0.07 for TOA, but -0.41 for the atmosphere (5% significance level is about 0.46). The Atlantic MHT variations along the equator are not only small, they are also mostly not significantly correlated with others except for the Indian Ocean (-0.66), while covariability with the Pacific (-0.36) is not significant. The Pacific and Indian Oceans are weakly (not significantly) correlated (0.27) and the atmosphere is correlated (-0.39 ; also not significant) with the Pacific. The MHT in the Indian and Pacific Oceans seem to vary together (Fig. 11), with peaks more or less coinciding from 2002 to 2015, but that relationship is countered by the huge ITF effects in 2016 that go in opposite directions, as detailed above in sections 3a and 3b, although those effects are much greater farther south. Ma et al. (2019) note that enhanced ITF heat advection is the largest contributor to warming of the southern Indian Ocean during La Niña, while overall most of the anomalous ITF heat advection is compensated by the meridional temperature transport anomalies across the southern boundary during both El Niño and La Niña. However, they did not include the 2015/16 El Niño event.

4. Concluding remarks

In this study we included effects of the ITF on the MHT within the ocean, and examined the consequences. It enables the Indian and Pacific Ocean contributions to be separated, although they are inextricably linked by the conservation of mass and the “island rule” of Godfrey (1996). The ocean heat transport is strongly associated with the mass transport in the ITF, and accordingly the mass budgets for the Indian and the Pacific Oceans are not closed. This leads to some arbitrariness in terms of how the heat transports are described as the total depends on the reference temperature, chosen here to be 0°C . The ITF tends to be highly variable and somewhat in synch with ENSO with regard to the MHT. Using the ORAS5 anomalies, which may be slightly overestimated based on the net mass transport, we have been able to separate out the MHT from the two oceans and thereby generate both the mean annual cycle and 12-month running mean time series of anomalies of MHT for the first time.

Given the time series, we have then been able to explore the MHT relationships with ENSO and marine heat waves in the south Tasman Sea. The latter have bloomed in recent years, notably in 2015/16 and again in 2018/19, both times of El Niño events. The ITF responds

to ENSO variations, but the changes were especially large and unprecedented during 2015/16 when the ITF dropped by 0.4 PW in terms of heat transports westward and southward. At the same time the East Australia Current was strong and penetrated farther south into the Tasman Sea than normal. Given the requirement for a return mass flow around Australia, it is perhaps not surprising that these two events should be linked, but it appears that this link was the exception rather than the rule. Atmospheric circulation anomalies were favorable to allow this to occur whereas much more commonly during El Niño events they are not. Nevertheless, this interconnected change over thousands of kilometers in the ocean outside of the deep tropics is of considerable interest. It certainly had a profound influence on the marine biology and fish (Oliver et al. 2017).

There is a very large mean annual cycle in ocean MHT of up to 8 PW in and somewhat north of the equatorial region, especially in the Pacific. Accordingly, the annual mean is a fairly small residual, and on the equator the value is -0.3 ± 0.1 PW in the Pacific. However, the AMOC contributes to a strong northward MHT across the equator in the Atlantic of 0.75 ± 0.02 PW. Consequently, the net ocean heat transport across the equator is northward of 0.2 ± 0.1 PW. This heat flows into the North Atlantic and Arctic. Meanwhile, the atmosphere transports heat southward by more than enough to counter the net ocean northward contribution, so that the net transport at the TOA is also southward. However, there is an additional southward transport of heat on the order of 0.1 PW that is absorbed in the Southern Hemisphere ocean at a rate much greater than the heating of the northern oceans, leading to an imbalance in the equatorial crossing of heat/energy. The estimate of this value based on our MHT computations is about half that estimated from separate OHC changes, but within the error bars. Accordingly, a reasonable closure is obtained, providing confidence in the results overall. Nonetheless the MHT variability in the Pacific is large and the anomalous MHT in 2016 is far outside of previous values.

The Pacific and Indian Ocean MHT across the equator tend to be somewhat coherent, in spite of the ITF working in opposite ways in each, and they leave a small residual effect on the TOA radiation implied MHT. The MHT is highly correlated with ENSO, with the ONI leading by about 3–4 months. The Atlantic variability is much smaller. The full implications of such large MHT anomalies need to be explored further, especially in the contexts of marine heat waves in both hemispheres.

Previous studies of the interhemispheric transport have not accounted for the differential heat uptake in the two hemispheres, which means that the sum of the

atmosphere and ocean equatorial transports do not sum to that at the TOA. The exceedingly large variability in Pacific MHT associated with ENSO, also noted by Forget and Ferreira (2019), should be taken into account in the many studies of cross-equatorial transport, and we have provided an updated set of numbers for the various components and the total.

It has taken many years for the datasets in the atmosphere, ocean, and satellite-based radiation to improve sufficiently to enable the kinds of observationally based estimates of MHT with sufficient confidence and quantified uncertainty to be credible as time series. Datasets continue to improve, and new atmospheric reanalyses will enable more accuracy, for instance. Meanwhile, the estimates produced here provide a basis for evaluating model results and have raised a number of interesting science questions.

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