The Effects of Near-Inertial Waves on Ocean Heat Content and Transport

A Thesis

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by

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Certificate

This is to certify that this dissertation entitled *The Effects of Near-Inertial Waves on Ocean Heat Content and Transport* towards the partial fulfillment of the BS-MS dual degree program at the Indian Institute of Science Education and Research, Pune represents study/work carried out by **Medha Murti** at the Max Planck Institute For Meteorology under the supervision of **Dr. Noel Gutierrez-Brizuela**, Group Leader- Theoretical Ocean Dynamics, Climate Dynamics , during the academic year 2025–2026.

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Dedication

This thesis is dedicated to Gore Verbinski.

Declaration

I hereby declare that the matter embodied in the report entitled ”The Effects of Near-Inertial Waves on Ocean Heat Content and Transport” are the results of the work carried out by me at the Max Planck Institute for Meteorology and Earth and Climate Sciences Department at the Indian Institute of Science Education & Research (IISER) Pune, under the supervision of Dr. Noel Gutierrez-Brizuela. The work has not been submitted elsewhere for any other degree.

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Contents

List of Figures

Abstract

Previous work on the effects of tropical cyclones and near-inertial waves on the ocean and climate has mainly focused on the impacts of increasing diffusivity within the oceanic mixed layer. In this thesis, we show that near inertial waves generated both by tropical cyclones and midlatitude storms constitute an import source of turbulent kinetic energy and diffusivity even in and below the oceanic thermocline, and lead to large scale re-arrangements in heat content between different ocean basins and hemispheres. We also show that near-inertial wave energy is able to penetrate the deep ocean, requiring future studies to consider the impacts of these waves on much longer timescales than a few decades. This work is accomplished using IDEMIX, a novel parameterisation for internal waves developed at the Max Planck Institute for Meteorology, and the XPP configuration of the ICON model.

Acknowledgments

AI Use Acknowledgement: No Generative AI was used in this thesis.

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Chapter 1

Introduction

1.1 A Brief Introduction to Near-Inertial Waves

Near-inertial waves are a type of internal wave with frequencies at or around the local inertial frequency. Inertial oscillations are the dominant response of the ocean to sudden bursts of wind, and near inertial waves are therefore one of the most energetic frequency bands of ocean current variability. Tropical cyclones and midlatitude storms can supply significant amounts of energy to near-inertial motion (Nilsson, 1995), through winds that rotate at frequencies close to the local inertial period. As the currents induced by these winds oscillate in the mixed layer, their convergence and divergence pumps its base (Gill, 1984), setting up pressure gradients that allow the propagation of NIWs even beneath it (D'Asaro et al, 1995). Lower modes (larger horizontal wavelengths) tend to propagate horizontally away towards the equator much faster than higher modes, and as these modes are the most energetic, are able to carry significant amounts of energy further away. Large vertical shearing in these waves then causes turbulence, and local mixing (Alford and Gregg, 2001, Alford et al 2016).

The mixing associated with near-inertial waves was consequently first examined as a possible source of the turbulent energy required to close the upwelling limb of the global overturning circulation. Denser water must be transformed to lighter water and moved back toward the surface in the deep ocean to prevent it filling with the densest possible water forming at higher latitudes, and this requires mixing, as outlined in Abyssal Recipes II (Munk and Wunsch, 1998)). Owing to the difficulties in obtaining long-term microstructure measurements of diffusivity and near inertial-velocities, large uncertainties in the spatiotemporal characteristics of near-inertial wave forcing and the eventual fate of the energy carried by these waves persist to this day. Their role in closing the overturning circulation, or in shaping any other large-scale circulation that regulates climate has therefore not yet been constrained.

1.2 NIWs and Climate

Jochum et al (2012) looked at the impacts of NIWs on the climate by introducing a parameterisation in CCSM4 that amplified near-inertial energy in the boundary layer, allowing a fixed fraction (0.15) of it to leave the mixed layer and propagate vertically downward, where it was then set to decay exponentially with depth with a scale of 2000m. The nature of this parameterisation meant that the resulting impacts of near inertial waves on mixing, and consequently heat content, below the thermocline were relatively small. Therefore, the study focused primarily on the effects of increased boundary layer mixing on the mean state of the climate, in terms of changing patterns of sea surface temperatures.

The study found SST cooling in the subtropics and just off the equator, as a result of increased mixing at these locations. The tropics, and in particular the eastern equatorial Pacific, warmed as a result of weakened poleward Ekman transport from the region and the convergence of anomalous heat pumped down in the off-equatorial regions. An increase in off-equatorial precipitation was also observed, as well as weakening midlatitude wind stress. Contrary to the hypothesis presented in Munk and Wunsch (1998), the study found negligible change in the ventilation of the thermocline and subthermocline, as well as in oceanic meridional heat transport (both in the shallow Pacific subtropical cells and in the deeper AMOC). This suggested that either the impacts of near-inertial waves on the ocean beneath the boundary layer were negligible, or that they shaped it through mechanisms other than global overturning.

1.3 Storms and Ocean Heat Transport

Many other studies (Korty et al 2008, Jansen and Ferrari 2009, Pasquero and Emanuel 2008, Jansen et al 2010, Fedorov et al 2011, Li and Sriver 2018, Vincent et al 2013) have examined the role of tropical cyclones in ocean heat transport and storage, although without explicit mention of near-inertial waves as contributors to the vigorous upper-ocean mixing triggered by these storms. According to the heat-pump mechanism (proposed in Emanuel, 2001), heat is mixed downward and out of the mixed layer during cyclones, isolating it from the cooled surface, which then absorbs heat from the atmosphere until its temperature is restored to pre-cyclone values. The excess heat stored in the subsurface as a result can be moved by geostrophic transport out of the deep tropics or advected along isopycnals back toward the equator, depending on the latitude band of these cyclones

(Jansen and Ferrari 2009).

Estimates of heat uptake via this mechanism for the present climate are large (1.4 petawatts from only a year of tropical cyclones, Emmanuel 2001), indicating that it could comprise a significant fraction of annual oceanic meridional heat flux. However, some studies (such as Jansen and Ferrari 2009,) also reported that the increase in heat transport was less a consequence of increasing ocean heat uptake in the cold wake of a cyclone, and was instead primarily due to increased shallow overturning (an increase in diffusivity creates an anomalous upwelling, assuming a zeroth order balance between upwelling and diffusion in the subtropical gyre, which increases northward heat transport).

Studies applying idealised and uniform mixing in the upper ocean (usually in upper 300m or so), found an increase of about 30% in peak meridional oceanic heat transport, but in a warmer climate. Studies like Li and Sriver 2018, Scoccimarro et al 2011, and Vincent et al 2013, on the other hand, which prescribed more realistic mixing from directly simulated tropical cyclones in the present climate, showed that the net effects on OHT were small enough to not perturb the annual mean by more than 1-3%. Li and Sriver 2018, in particular, discussed in detail the effects of tropical cyclones on the ocean, using 30 years of output from a TC-resolving coupled model to force an ocean-only model of nominal 1 degree resolution (not enough to resolve near-inertial waves).

They found increased subsurface heating north of the Kuroshio extension and in the eastern equatorial Pacific, as well as a slight cooling up to 500m between 30 and 35° N. The surface cooled in the western Pacific from the equator up till 50° N. They noted that meridional overturning and heat transport increased by about 3% and 2.5% respectively, a significantly smaller change than in the idealised studies mentioned in the paragraph above. This evidence suggested that storms, and the associated increasing upper ocean diffusivity (which was the focus of both the studies looking at storms and the studies looking at NIWs), had a relatively small impact on OHT.

1.4 Observational Evidence

Observations from north of the midlatitude winter storm track (Alford et al, 2012) indicate that anywhere between 12 to 33% of energy in the near-inertial band crosses 800m to reach the deep ocean. The study also found that dissipation is very weak between 200 and 600m, but significant **at** both of these depths. It was difficult to infer the depth-distribution of vertical mixing associated with these waves from only two years of observations at a single location, with significant variation between the two years. However, this estimate is notable because Ocean Station Papa (the mooring from which these observations were collected, at 50° N and 145° W) is in a relatively calmer area of the storm track with lesser wind forcing, suggesting that the amount of near-inertial energy reaching the deep ocean might be significant.

A similar observational campaign in the tropical Pacific (Brizuela et al, 2023) showed that mixing induced by near-inertial waves after tropical cyclones was capable of transferring heat across the permanent thermocline (ie, deeper than 200-300m) for weeks after the cyclone had passed. Integrated over only a small fraction of the area affected by the three cyclones studied in the campaign, the study found that almost 0.015 PW of heat crossed the 22° isotherm, reaching depths at which it could move towards the equatorial Pacific or higher latitudes without being re-entrained into the wintertime mixed layer (Holmes et al 2019 (a)). Their work suggested that downward heat transfer by these waves in the aftermath of tropical cyclones could be a mechanism through which these storms could impact remote locations. Both observational campaigns indicate that the near inertial waves are an important source of turbulent kinetic energy even beneath the first two hundred or three hundred meters, and should be considered in studies of the impacts of ocean storms to get a complete picture of their effects.

1.5 Intermediate Depths and Ocean Heat Transport

The standard treatment of ocean heat transport (an integral over volume of meridional velocity times temperature) ignores the fact that most of the heat being circulated by the ocean moves in loops of the overturning circulation without being deposited at a particular location (Forget and Ferreira 2019). This heat is not directly relevant to the climate, so using this measure often obscures more important pathways of heat transport that are not associated with volume transport of water in the ocean. It also introduces a dependence on a reference temperature (0° C commonly, and it is not apparent why this should be the reference). Constructing a 'heat function' to remove the signal due to these ineffective heat loops highlights the role of the tropical Pacific in taking up and exporting heat poleward to lower temperatures and to other basins, and of the Indian and Atlantic basins in cross-equatorial heat transport. Forget and Ferreira (2019) used the Helmholtz decomposition to split ocean heat transport into a a rotational component and a divergent component (important, because the divergence and convergence of ocean heat transport implies heat release and uptake to and from the atmosphere respectively). The heat function in their paper was thus the divergent component of ocean heat transport.

Holmes et al 2019 (a) used a similar heat function called the internal heat content transport, and observed that diathermal heat transfer across isotherms (peaking at the 22° isotherm) is necessary to drive ocean heat transport: climatological surface heat fluxes act to warm the tropics and cool the extratropics- heat is therefore gained in one temperature class and lost in another, so in equilibrium there must be heat transfer from one temperature class to another: ie, diathermal heat transport. This diathermal heat transport is ultimately achieved by small scale diffusion in the ocean across temperature gradients. In the context of their work, diffusivity sources at greater depths (and therefore lower temperatures) in the tropics, such as that provided by near-inertial waves, become very important, since heat pumped across these isotherms must regulate heat transport to the extratropics in steady state.

Holmes et al 2019 (b) showed that heat-uptake and diathermal heat transfer in the Indopacific basin enabled northward ocean heat transport in the Atlantic. They computed the transport of internal heat content and showed that heat transferred by the subtropical cells in the Pacific is important because it spans a large range of temperatures (meaning heat is transferred across more temperature classes), the lower end of which overlaps with the temperature range at which Atlantic heat transport occurs. Since surface heat uptake is dominated by the Pacific cold tongue, it stands to reason that there must be both heat transfer between basins and across isotherms. In particular, diffusive heat transferred across the 15° isotherm in the Indopacific is important, as most heat transport past 50° N in the North Atlantic Deepwater Cell occurs at or below this temperature (Holmes et al 2019 (b)).

Previous studies (such as Jochum et al 2013 and Li and Sriver 2018) have found negligible changes in ocean heat transport calculated in the standard manner on shorter timescales. Knowing that the heat transport associated with volume transport of water in the ocean may not be as significant to the climate as was previously thought, and that the presence of diffusivity at depths is less likely to affect the magnitude of general circulations that are primarily surface-forced (wind and buoyancy), it is important to re-examine the question of the importance of near-inertial waves and storms in ocean heat transport. By constructing a similar heat function, we can isolate the effects of the diffusive fluxes on the diathermal heat transfer.

1.6 Connecting Observations and Previous Modelling Work

Past experiments leave us with a very unclear picture of whether and how NIWs may shape large scale climate. Jochum et al 2012 presented important impacts on precipitation patterns and SST, but did not focus large-scale oceanic changes possibly underpinning these changes. Studies of the storm-induced ocean heat pump, on the other hand, identified a very clear mechanism for the impact of storms on climate, but the models they used to do this were idealised and did not incorporate near-inertial waves into their reasoning. The models that did attempt more realistic configurations also mostly dealt with tropical cyclones, and did not consider the effects of midlatitude storms. They also chose to focus on increased mixing only in the upper ocean, ignoring inertial wave energy as a potential source of diffusivity deeper than 200m in the tropics and extratropics.

The aim of this thesis is to expand on the work done by previous studies linking relatively small-scale diffusive processes to larger climate effects, using an updated and more realistic parameterisation for internal wave-driven mixing. IDEMIX (Bruggemann et al 2024, Olbers and Eden 2013), is a module that explicitly accounts for the wave-wave interaction, refraction, advection, and dissipation of internal waves. The contribution of internal wave energy to turbulent kinetic energy is determined without needing to artificially inject energy into the climate system to maintain a set diffusivity, unlike in standard parameterisations that assume a constant background diffusivity always provided by internal wave breaking.

With this new, energetically consistent parameterisation, and in view of observations that show the deep penetration of near-inertial waves and the resulting deepening of storm-driven heat transfer, this thesis re-examines the question of the impacts of NIW-driven mixing. Does the presence of near-inertial wave induced mixing below 200m affect poleward ocean heat transport by leaking heat out of the thermocline region, which is usually assumed to be adiabatic? Given that intermediate depths were shown to be coupled to deep circulation in the previous section, how does the increase in deeper mixing affect heat redistribution between different temperature classes?

We chose to focus specifically on the Pacific, as the length of the timeseries is too short to fully explore Atlantic ocean heat transport, which is dominated by the much deeper and slower Atlantic Meridional Overturning Circulation. We also hope that a longer timeseries of 150 years, compared to Jochum et al 2012 (40 years of data), helps to reinforce some of their results statistically.

Chapter 2

Methods

2.1 Model and Experiments

To determine the impacts of near-inertial waves on the climate, two fully coupled ICON model experiments in the XPP configuration were run (Müller et al, 2025). The XPP configuration was designed for extended simulation and climate prediction. The model was run for an R2B4 atmospheric grid and an R2B6 oceanic grid, roughly equivalent to an 80km and 40km atmospheric and oceanic resolution respectively (not an eddy resolving configuration).As previous experiments conducted with IDEMIX have used ocean-only models, this is also the first IDEMIX setup (to our knowledge) to consider ocean-atmosphere interaction mediated by near-inertial waves.

The first experiment, using IDEMIX with the near inertial wave component turned off (henceforth NIW OFF) was initialised from an 850-year pre-industrial control run with a different mixing scheme, and stepped forward for 500 years, until the drift in global mean upper ocean temperature reduced. At this point, the run was branched, with near-

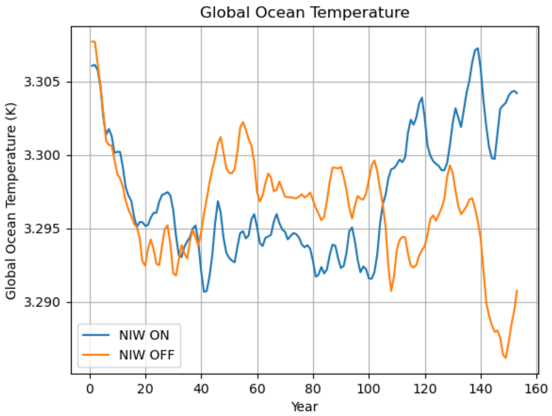


Figure 2.1: Global Oceanic Temperature

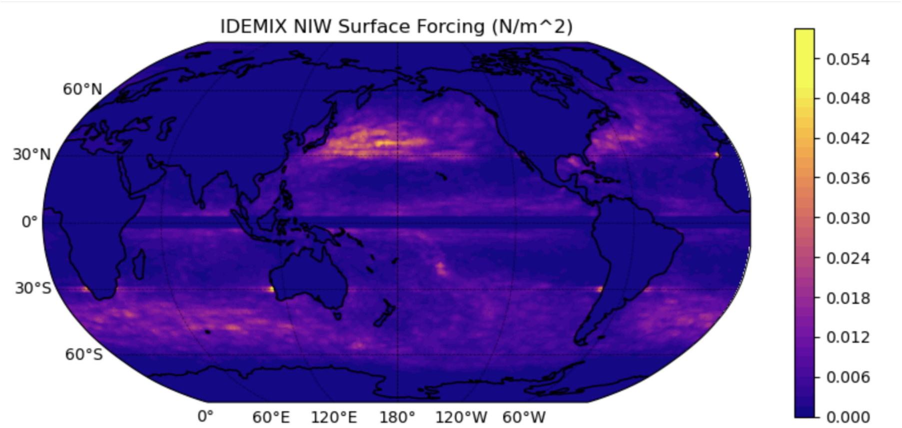


Figure 2.2: IDEMIX Surface NIW ON Forcing

inertial wave component of IDEMIX turned on (henceforth NIW ON) for one branch, and both were stepped forward for a further 150 years. Global upper ocean temperature and TOA radiation did not change significantly between the runs, but the model still does show a slight drift in the deep ocean, which is why the study will focus on the shallow overturning circulation of the Pacific and not deeper circulations like AMOC. In Figure 2.1, we can see that the two runs begin to diverge after about the first 30 or so years- but the changes are still very small.

2.2 IDEMIX

IDEMIX is based on the radiative transfer equation for internal wave energy integrated over wavenumber space, and assuming horizontal homogeneity. The version of IDEMIX used in this study consists of lee wave mixing, tidal mixing, and near-inertial wave mixing. Given a particular distribution of stratification and the externally prescribed forcing functions (surface forcing based on the magnitude of wind stress fluctuations, and bottom forcing based on the interaction of barotropic tides with topography to produce tidal internal waves), internal wave energy at all points can be calculated. The energy dissipated by the internal waves (the dissipation term in the internal wave energy budget) then becomes part of the turbulent kinetic energy budget in the shear production term. Vertical and horizontal group velocities are calculated assuming a spectral shape following the Garrett-Munk Spectrum. However, all of these quantities, as well as the energy dissipation, depend on the stratification.

From Bruggemann et al 2024, the radiative transfer equation for the internal wave energy density is given by:

$$\partial_t E_{\mathrm{iw}} = \partial_z \left(c_0 \tau_v \partial_z (c_0 E_{\mathrm{iw}}) \right) + \nabla_h \cdot \left(\tau_h v_0 \nabla_h (v_0 E_{\mathrm{iw}}) \right) - \epsilon_{\mathrm{iw}}. \tag{1}$$

E_{iw} is the internal wave energy density, and c_0 and v_0 are the vertical and horizontal group velocities, and the other symbols are prescribed constants that take care of wave-wave interaction and lateral homogenisation. The dissipation term is given as:

$$\epsilon_{\mathrm{iw}} = \mu_0 \frac{f_e}{m^*} N^2 E_{\mathrm{iw}}^2 \tag{2}$$

Where m^* is a parameter that also depends on the stratification (N). As a result, internal wave propagation and ocean stratification are coupled, allowing the climate and the waves to interact directly. IDEMIX's treatment of internal waves also relies on fewer assumptions of their properties: for example, it does not fix a penetration fraction or depth-scale of near-inertial energy, as was done in the other studies mentioned in the introduction (instead, it calculates vertical propagation based on stratification). IDEMIX also uses a more realistic spatial distribution of wind forcing than some of the more idealised studies from section 1.0.3. However, this forcing at the surface is constant, and does not evolve with the model's climate state, and horizontal propagation is not explicitly resolved. Previous work (see Manucharyan et al 2011) has also shown that the intermittence of mixing is an important factor in determining its impact; and since near-inertial waves are highly intermittent (Alford et al 2016), the results should be viewed in consideration of these factors.

2.3 A Note on the Analysis

Significance tests (Students t-tests unless mentioned otherwise) were conducted on a 30-year rolling average, to eliminate the effects of high-magnitude short-term variability. Since there were barely any differences between the two runs in terms of global temperature initially, it was assumed that there was no need to exclude the beginning of the NIW ON time series as spin-up time beyond the first five years (not shown in any of the time series). Any variables presented in a timeseries are (unless explicitly mentioned otherwise) are a difference of NIW ON and the time mean of NIW OFF.

Chapter 3

Results and Discussion

3.1 Changes in Internal Wave Energy

Internal wave energy increases at all depths, indicating that near-inertial waves add energy to the system (from figure 3.1, about a 24% increase in the surface values of internal wave energy, even higher below), and are able to penetrate quite deep. The figure therefore also suggests that a 160-year time series might be too short to properly assess the impacts of these waves- if a significant fraction of their energy is dissipated into the deep ocean, impacts are much more likely to show up later than the first century or two, as the deep ocean adjusts to forcing quite slowly, (on a scale of a thousand years). Even so, changes in the upper 1000m are significant enough to be worth examining, and a more detailed analysis of changes occuring beneath this depth is beyond the scope of this thesis, though they will be touched on briefly in section 3.3. To put numbers to it, the fraction of excess near-inertial wave energy (between the NIW ON and NIW OFF case) in the surface layer that crosses 600m (global average) is about 0.58, and the fraction crossing 800m is about 0.48, which is higher than but still within a reasonable limit of the 0.12 to 0.33 figure from Alford et al 2012. In comparison, the parameterisation employed by Jochum et al 2012 allowed about 10% of the near-inertial energy at a given location to cross 800m. It is difficult to say which estimate is more accurate, but in either case, it is a confirmation of Alford et al 2012's finding that near inertial wave energy is significant in the deep ocean.

In both the Pacific and Atlantic basins, near inertial wave energy is concentrated in specific latitudinal bands (shown in Figure 3.2)- around the equator (due to tropical cyclones, and a low coriolis frequency that means inertial waves can be excited by dominant low frequency disturbances), towards the west at the midlatitudes (due to the presence of midlatitude storm tracks in these regions), and at the southern edges of the basins (possibly due to overlap with the Southern Ocean storm tracks). The depth structure of

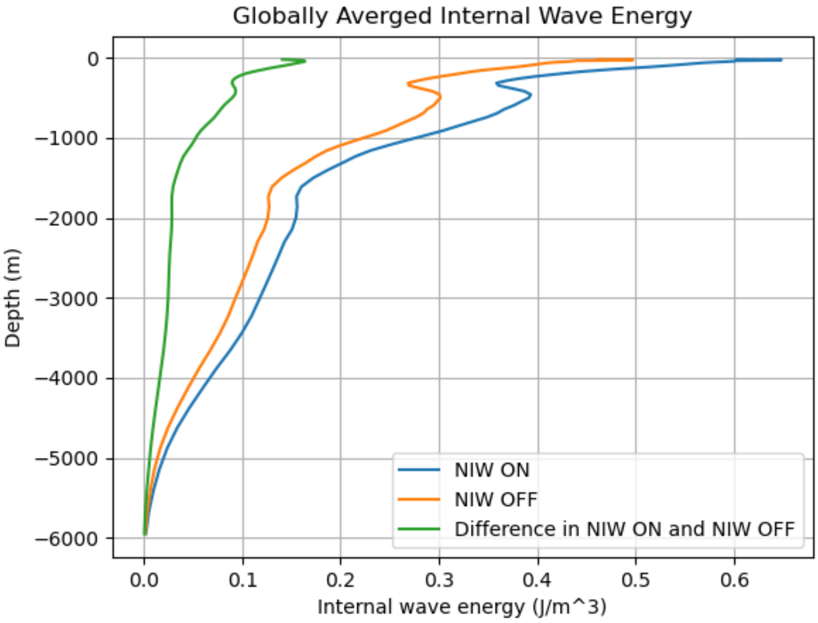


Figure 3.1: Globally Averaged Near Inertial Wave Energy for NIW ON and NIW OFF and their differences

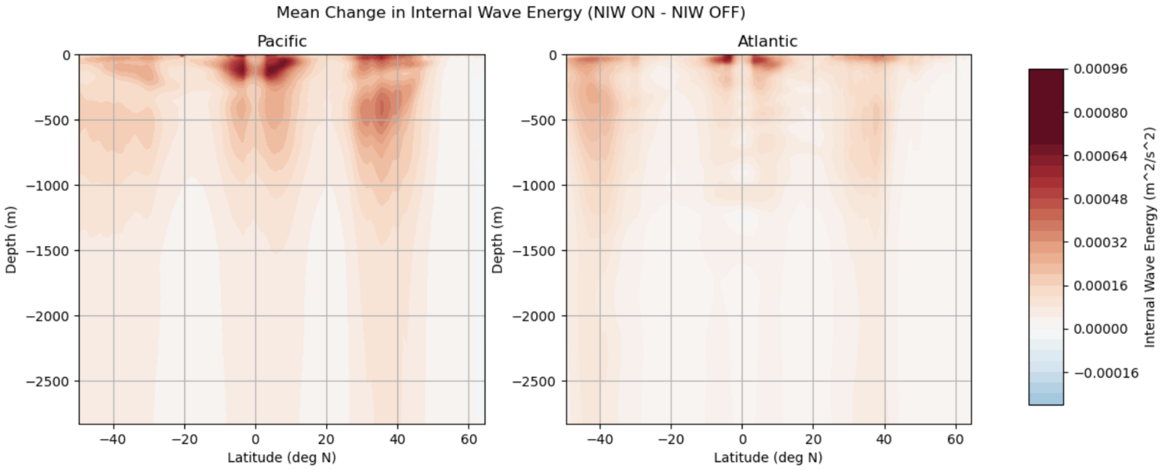


Figure 3.2: Difference in near-inertial wave energy for Atlantic and Pacific Basins

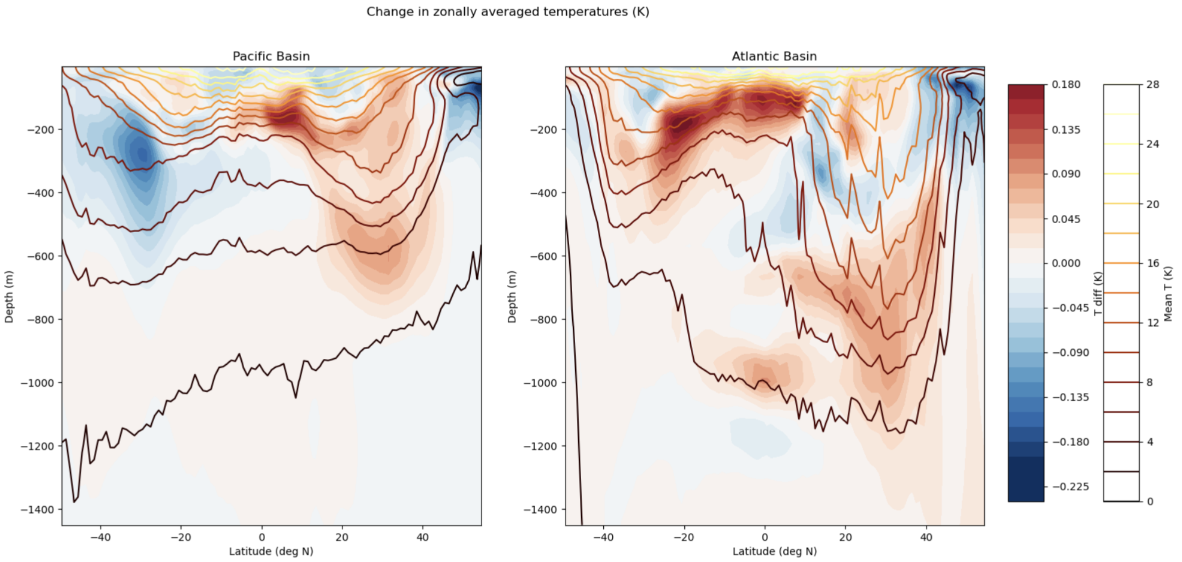


Figure 3.3: Differences in zonally averaged temperature between NIW ON and NIW OFF for the full timeseries in the Pacific and Atlantic basins

near-inertial wave energy in the midlatitudes is also interesting; in both basins, it tends to show two local peaks, one in the upper 100m, and one slightly deeper, between 400 and 500m, which could be related to the stratification structure.

3.2 Changes to the mean state, emphasis on the Pacific

Heat is stored quite deep in the subtropics and extratropics (primarily between 20 and 40 N and in the north-western Pacific), with significant increases (at a 95% confidence level, shown in Figure 3.4) in mean temperature occurring consistently between 500-700m in the extratropics. The peak of heat storage is slightly deeper than the peak of internal wave energy; in steady state, it is possible that the dominant balance between is between surface input and subsequent vertical propagation of internal wave energy, and dissipation; so the depths at which mean internal wave energy starts to decrease in the vertical corresponds to where less dissipation is taking place (as dissipation is proportional to internal wave energy squared, though it also has a dependence on stratification so this isn't a direct correlation) allowing for heat storage. The changes in temperature throughout the water column are small, but significant - the mean extra heat stored between 20 and 40 N in the NIW ON case when compared to the NIW OFF run is about 3.2e21 J, and the mean amount of heat in the NIW ON case is significantly higher than that stored in the NIW OFF case (t-test, p value 1e-11).

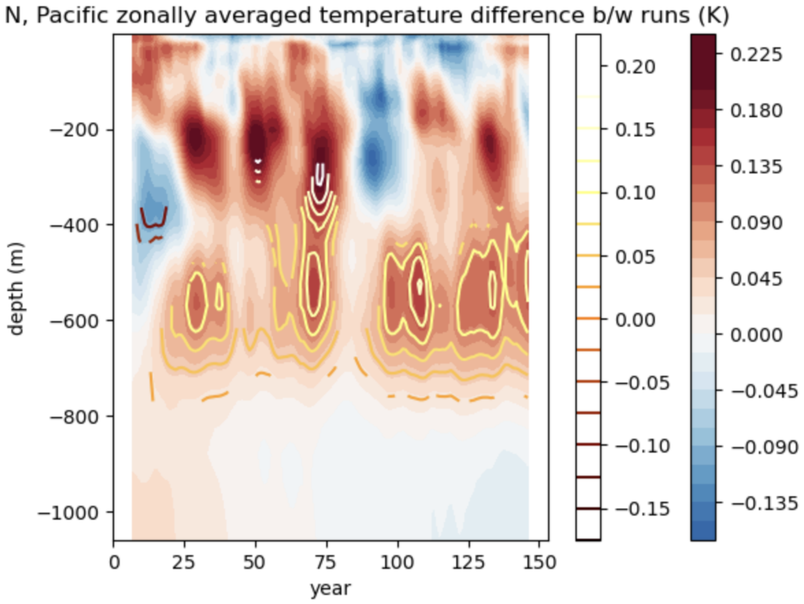


Figure 3.4: Temperature anomalies averaged over 25-40N, with contours of the temperatures anomalies plotted when they're significant at the 95% confidence level

To put this figure into context, the oceans have taken up about 4.3e23 J since pre-industrial times (Zanna et al, 2019)-averaging this over the area of the global ocean, we get about 7.9e21 J of heat uptake over the amount of area between 20-40 N in the Pacific. The introduction of near inertial waves thus results in the uptake of nearly half as much heat into this area as it has absorbed due to anthropogenic climate change on average. (Of course, the ocean has warmed very unevenly so an areal average may not have a physical significance, but this is a basic attempt at checking the relevance of the value.) Li and Sriver 2018 found cooling in this region that was similar in magnitude to the warming obtained through the addition near-inertial waves in the 150-400m region, and much lower below. The reversal of sign and increase in magnitude of the temperature change signal at higher depths indicates that near-inertial waves excited by tropical cyclones and midlatitude storms potentially play an important role in heat storage beneath the thermocline.

Contrary to our initial hypothesis, but similar to the studies like that of Li and Sriver 2018, we found no significant changes in mean peak northward ocean heat transport in the Pacific (about 1% decrease in the NH subtropics consistent with increased heat in the equatorward limb of the subtropical cell and cooling above, and a 2-3% increase in the midlatitudes consistent with) at any depth. This is possibly because the wind-driven subtropical cell extends to about 300m on average, with a peak in overturning in the upper 100m (Capotondi et al 2005), but near inertial wave-induced mixing primarily drives heat downward north of 30°N, where it is then subducted deeper than the bulk of the subtropical cell.

This is visible in Figure 3.5; temperature anomalies just below the surface north of 30°N are advected along isotherms in the upper 300 m or so. Reduced surface forcing in the subtropics also means that the direct impacts of deeper diffusivity at these latitudes in terms of diffusing heat downward from the poleward to the equatorward branch of the subtropical cell or leaking heat out of the subtropical cell beneath 200m is negligible when compared to the magnitude of OHT. However, this heat transport was calculated in the regular way (as an integral of velocity times temperature over depth and longitude), and since a large proportion of heat transport estimated like this consists of ineffective loops, it is possible that any effects on heat transport are being obscured because they are smaller compared to these standard values of heat transport. Heat converges at the tropics, as in previous studies, but the change in temperature of the equatorial Pacific is very small on the mean (as we have not analysed atmospheric output, such as off-equatorial windspeeds, we refrain from speculating as to why this might be the case). Changes in precipitation, mixed layer depth and surface wind speed are also very small (not shown), which is consistent with less additional near-inertial wave energy remaining in the boundary layer compared to Jochum et al 2012.

The Southern Pacific is also cooling on the mean, despite the presence of increased near-inertial wave energy at these latitudes that tends to lead to warming everywhere else. The cooling is very strong (as large in magnitude as warming in the tropics due to heat convergence), and also quite deep, but does not persist throughout the entire time-series, so may be part of some larger scale adjustment process. The reason for this cooling is not immediately apparent, but must be investigated further. It is worth noting that the heat uptake in the intermediate depths (400-800m) between approximately 20° to 35° N in the Pacific, though positive throughout the entire time series, is not constant, and increases monotonously with time: there's an initial steep increase in the first 30 years, followed by a smaller but constant rate of increase for the rest of the timeseries (curve not shown, but Figure 3.5 shows something similar).The dynamics of these intermediate depths is less well studied, and a longer time series is required to better understand what will happen to the significant amounts of heat accumulating at very low temperatures there.

The Atlantic shows shallower and stronger heating on average in the Southern Hemisphere, where near-inertial wave forcing is higher. However, the region of maximum temperature increase does not coincide with the region of maximum near-inertial wave forcing like in the Pacific basin, indicating that heat is converging at the region from other latitudes. The deeper Atlantic is also warming, and the heat signal can be vented

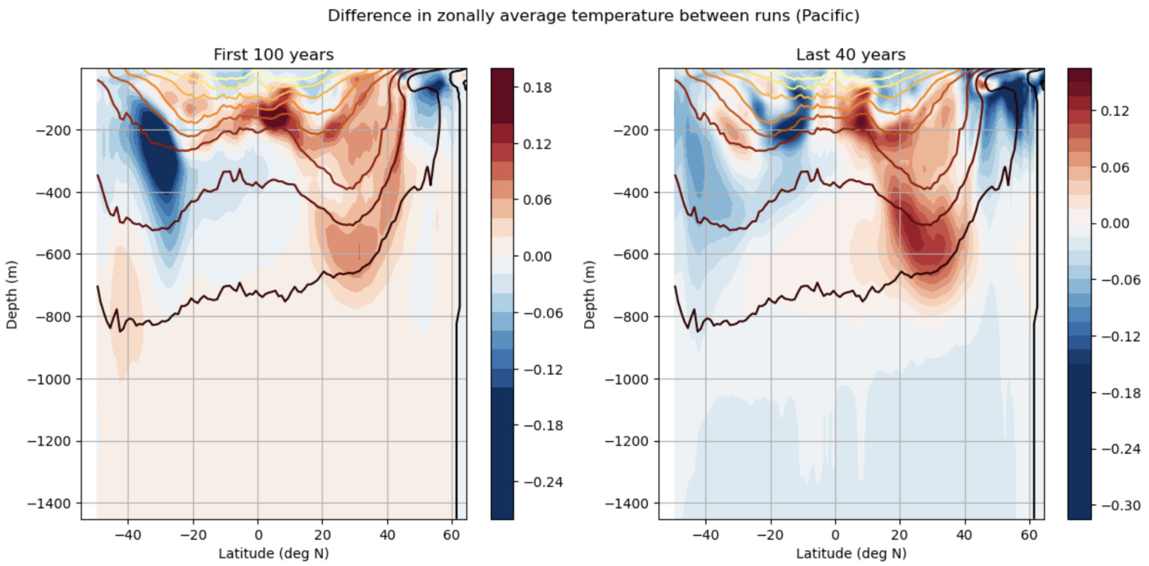


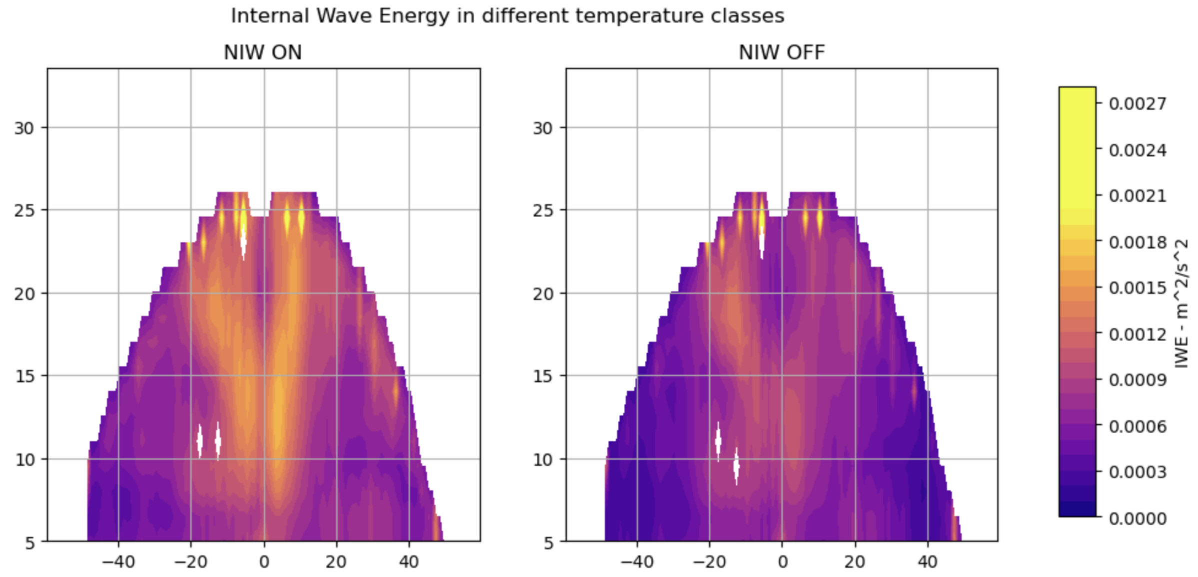
Figure 3.5: Same as in Fig 3.3 but for different sections of the time series, and with mean temperature contours plotted

at the surface along upward sloping isopycnals near the northern hemisphere midlatitudes, though the source of this heat is less clear (it could be a combination of diathermal heat transfer via mixing from higher temperatures above, and along isopycnals from the Southern Ocean).

3.3 Changes to Internal Heat Content

Observing the deep penetration of near-inertial wave energy, it is possible that near-inertial waves may provide some of the energy required to link the basins and upper-ocean circulation to intermediate depths and to the deeper ocean, as well as transfer heat from warmer to cooler temperatures in the Indopacific, thereby facilitating global ocean heat transport. In Near-inertial wave energy increases significantly even across the 15-10° isotherms in the tropical and midlatitude Pacific (Figure 3.6), potentially allowing for increased heat transfer across these isotherms. Since diffusive heat fluxes are not calculated online by ICON, increased cross-isothermal diffusive heat transfer in these temperature classes can be verified through the internal heat content framework.

Using the internal heat content framework of Holmes et al 2019 (a), we can assess the impacts of near inertial wave energy in transferring heat between different temperature classes (this has important implications for oceanic heat distribution and transport, as discussed in section 1.5, and it isolates heat transport that is directly relevant to the climate from ineffective loops associated with volume transport). Internal heat content is


Internal Wave Energy in different temperature classes

NIW ON

NIW OFF

Figure 3.6: Internal wave energy in different temperature classes in the **Indopacific** basin

a quantity independent of an arbitrary reference temperature, and is governed by a much simpler budget than regular heat content. The internal heat content framework provides a simpler way to diagnose the role of diffusive fluxes in diathermal heat transport by isolating the heat transferred directly from diffusion from that due to the cross-isothermal volume flux (water mass transformation) and its associated heat transfer, which is noisier and more difficult to calculate (Holmes et al 2019(a)). The transport of internal heat content at any given latitude is also equivalent to the heat function used by Forget and Ferreira et al, providing a simple physical interpretation for it. A brief derivation of this quantity is provided below, adapted from the same paper:

$$\mathcal{H}(\Theta, t) = \iiint_{\Theta'(x,y,z,t)>\Theta} \rho_0 C_p\, \Theta'(x, y, z, t)\, dV \tag{3.1}$$

This can also be expressed in terms of the volume of fluid at a temperature warmer than theta:

$$\mathcal{V}(\Theta, t) = \iiint_{\Theta'(x,y,z,t)>\Theta} dV \tag{3.2}$$

$$\mathcal{H}(\Theta, t) = \int_{\Theta}^{\infty} \rho_0 C_p\, \Theta' \left(-\frac{\partial \mathcal{V}}{\partial \Theta}\right) d\Theta' \tag{3.3}$$

Integrating the expression above by parts splits it into two terms:

$$H_I = H - H_E = \rho_0 C_p\, \mathcal{V}(\overline{\Theta} - \Theta) \tag{3.4}$$

$$\overline{\Theta}\ \textit{is the mean temperature in that temperature class} \tag{3.5}$$

Essentially, internal heat content is a simpler way to measure how much heat is stored at temperatures higher than (in a bubble bounded by) a particular bounding isotherm. The budget governing internal heat content above a particular isotherm:

$$\frac{\partial H_I}{\partial t}(\Theta,t) = F(\Theta,t) + P_I(\Theta,t) + M(\Theta,t) + I(\Theta,t) \tag{3.6}$$

F represents the forcing term at the surface in regions where the isotherms bounded by theta outcrop (sensible and latent heat fluxes, ice formation), P the additional heat due to surface volume fluxes at temperatures higher than the bounding isotherm (assumed to be very small, Holmes et al 2019 (a)), and M and I are the parameterised and numerical diffusion (including horizontal along-isopycnal diffusion if present) respectively. No distinction is made between these categories in this thesis, all diffusive fluxes are counted in one single diffusive term, and differences in the numerical diffusion term shouldn't be significant as we're comparing two runs which have identical underlying numerical models.

$$H_I(\Theta,t_f) - H_I(\Theta,t_0) = \int_{t_0}^{t_f} (F(\Theta,t) + P_I(\Theta,t) + D(\Theta,t))\,dt \tag{3.7}$$

The last 50 years of the 150-year long time-series are used in this analysis. The change in internal heat content between the two runs is used to determine an average rate of near-inertial wave driven heat transfer into lower temperature classes (12-15 ° C). Surface fluxes and internal heat content are both binned in temperature at 1.5 ° C intervals, and diffusion is calculated as a residual of the change in internal heat content and integrated change in surface heat fluxes. It should be noted diffusive fluxes aren't stored by the model and the temperature binning of the surface fluxes and internal heat content was not done online but rather from but annual averages. The diffusive term was calculated as a residual from the other terms and at an annual timescale, which decreases its reliability as all of these processes exhibit significant seasonal and sub-seasonal variability. As a sanity check, however, we observe that diffusive heat transfer tends to zero at lower temperatures.

Estimating the budget for this quantity shows that diffusive heat fluxes due to near-inertial waves transfer the maximum amount of heat from temperatures higher than about 22° to temperatures lower than about 15°.The rate of heat transfer across the 15 ° isotherm is about 0.014 PW. From the inset from Holmes et al (2019), we see that the heat transfer provided by background diffusivity (near-inertial wave breaking is usually parameterised to be a part of background mixing) at the 15 ° isotherms is about 0.3 PW (subtracting the thin dashed line representing the diffusive diathermal heat fluxes with no background diffusivity from the solid red line representing the control run). Diffusivity

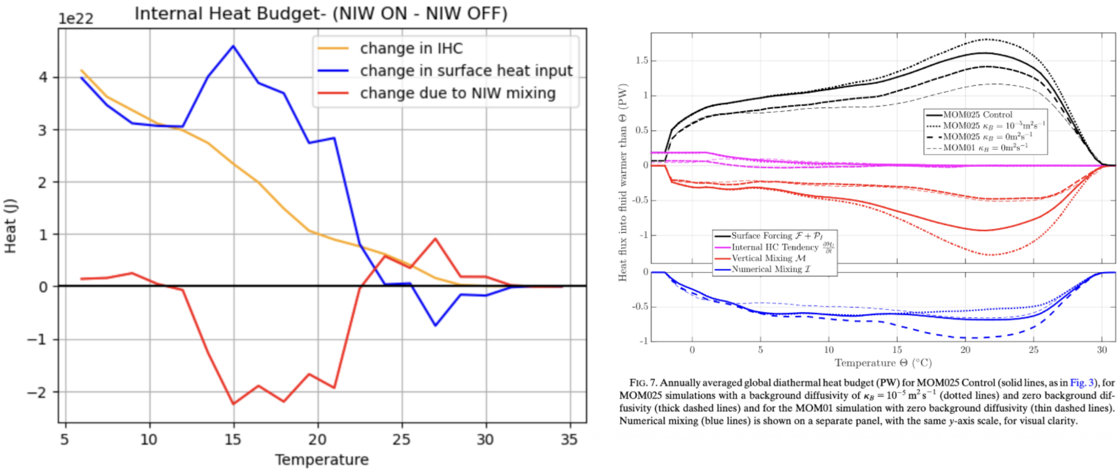


FIG. 7. Annually averaged global diathermal heat budget (PW) for MOM025 Control (solid lines, as in Fig. 3), for MOM025 simulations with a background diffusivity of $\kappa_B = 10^{-5}\,\mathrm{m^2\,s^{-1}}$ (dotted lines) and zero background diffusivity (thick dashed lines) and for the MOM01 simulation with zero background diffusivity (thin dashed lines). Numerical mixing (blue lines) is shown on a separate panel, with the same y-axis scale, for visual clarity.

Figure 3.7: Left: Difference in **global** temperature-binned internal heat content between runs, difference in heat content change due to surface fluxes and due diffusive heat transfer. Right: Annual average of the heat transfer rates across different isotherms.

provided by near inertial waves could therefore account for 5% of the energy required for heat transfer across the 15 ° isotherm. A caveat of this analysis is that the comparison isn't exactly fair-the same diagram (3.7 b) for a different model like ICON could look fairly different, however this is a first attempt at determining the significance of the changes brought about by near-inertial waves.

3.4 Basin-scale adjustment

To once more consider the effects of near inertial waves on individual basins rather than a global average, we can look at how the addition of near-inertial waves causes a rearrangement of heat between the different hemispheres and basins of the global ocean.

The global mean impact on the temperature structure is to move heat deeper and to lower temperatures, as observed in the previous section: the surface cools, and there's a maxima in warming up at about 180m; the second, deeper peak in internal wave energy from Figure 3.1 moves heat even deeper, from 200-500m to about 600-1000m. In contrast, Li and Sriver 2018 found a surface cooling and a single peak in subsurface warming at about 100m, and slight cooling below until about 500m. However, their global temperature changes (ie, the orange plot in panel 1 of Figure 3.8) in the upper ocean were an order of magnitude larger than the values we obtained through the addition of near-inertial waves- once again suggesting that the most significant impacts of near inertial waves appear at greater depths. Particularly striking is the warming of the Atlantic in

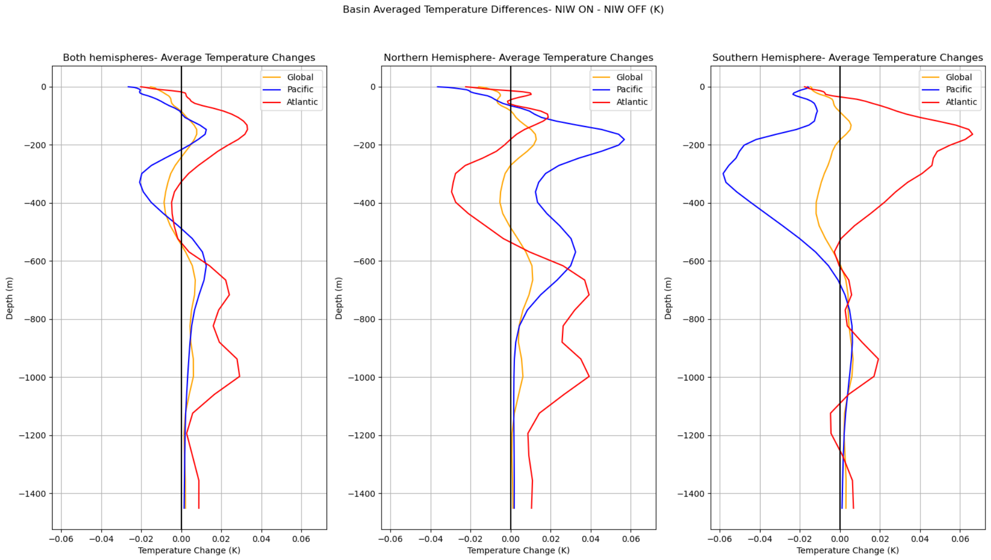


Figure 3.8: Hemispherically integrated basin-wise changes in mean vertical temperature structure

the northern hemisphere at depths where heat transport is dominated by the much slower AMOC (Atlantic Meridional Overturning Circulation).

However, this simplistic global average obscures the more complex spatial structure underlying the global mean changes- while the global average matches the rough structure of temperature changes observed in the northern hemispheric parts of both the Atlantic and Pacific basins, the southern hemisphere shows a completely different pattern-strong cooling in the Pacific and strong warming in the Atlantic, both with a fairly deep subsurface peak To explore this further, we can look at the connections between the basins in terms of cross-equatorial heat transport.

Referencing figure 3.9 - in the Pacific, heat content reduces in the Southern Hemisphere, and initially increases in the Northern Hemisphere before decreasing later. However, there is also drift in deep ocean temperatures in both models in the Indopacific, which may be generating the apparent decrease. The northern Pacific surface in NIW ON is also losing heat relative to NIW OFF for most of the time series, (a mean decrease in downward heat flux of about 7% on the NIW OFF case mean flux). This is interesting, because even though there's a net storage of heat in the north Pacific in NIW ON relative to NIW OFF (6e21 J, statistically significant), this heat is not coming from the atmosphere over the north Pacific. Northward cross equatorial transport must therefore be increasing on the mean or heat loss through the Bering Strait must be decreasing (this heat transport is two orders of magnitude lesser than mean cross equatorial heat transport, so the North Pacific can be considered to be a closed basin on its northern edge). Increasing Pacific

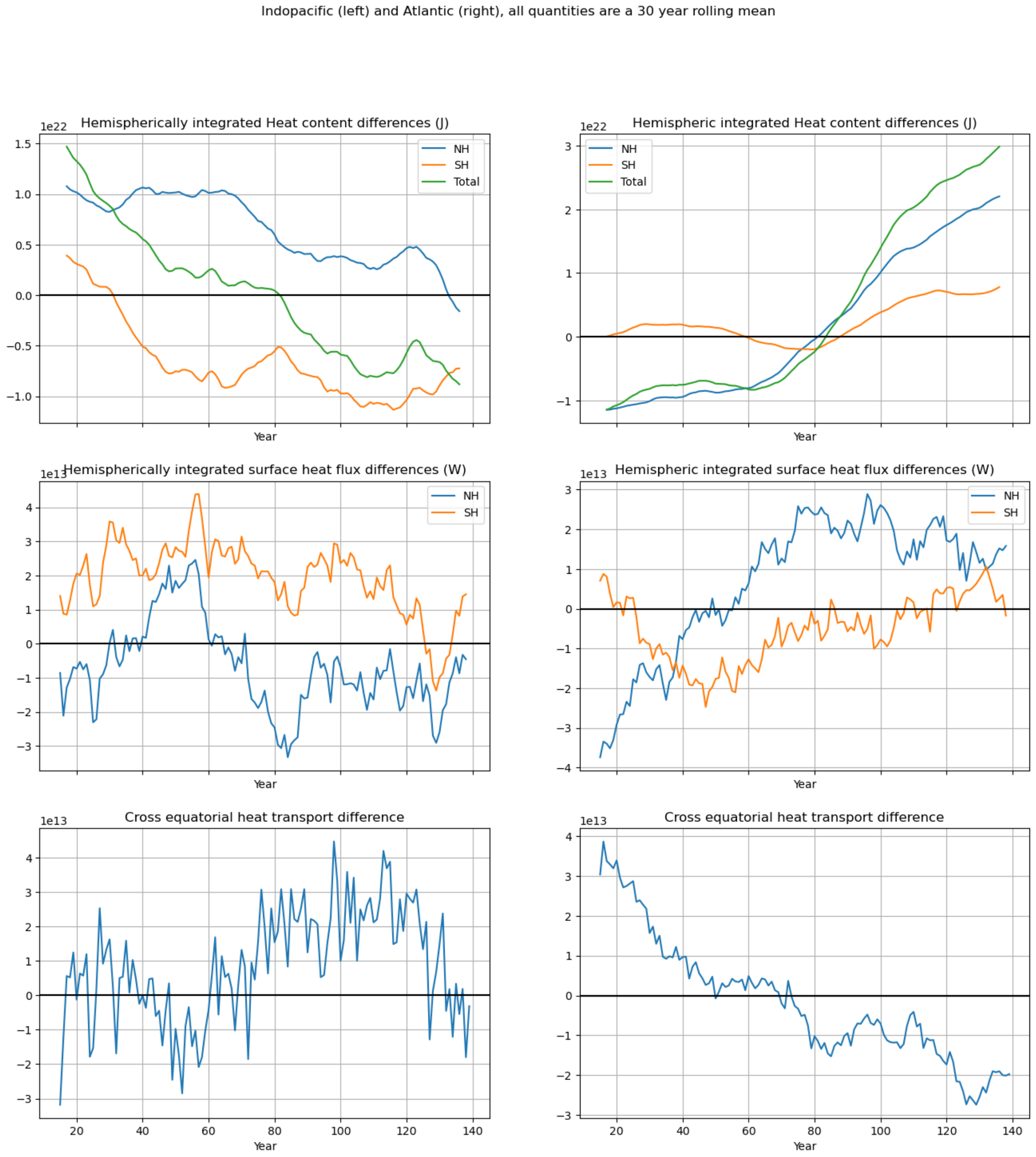


Figure 3.9: Hemispherically integrated changes in heat transport, heat content and surface heat flux between NIW ON and NIW OFF (NIW ON - mean of NIW OFF)

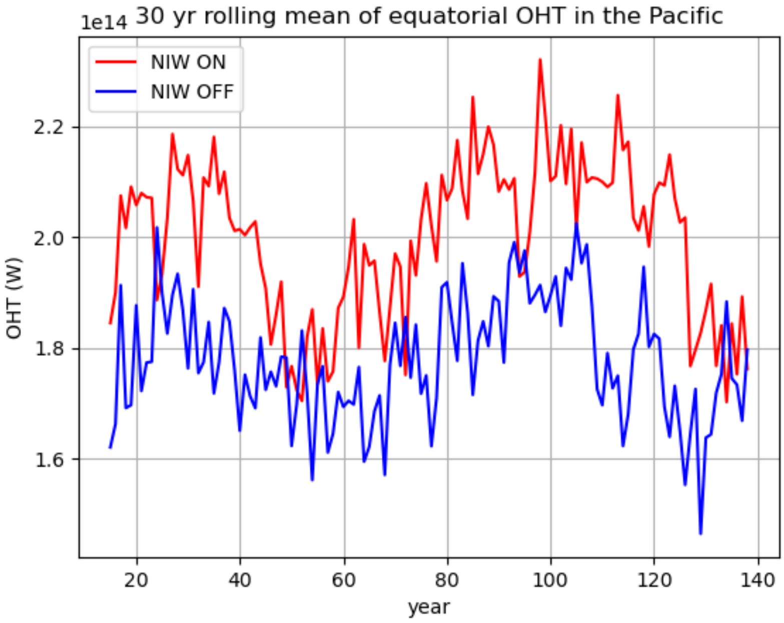


Figure 3.10: Cross equatorial Ocean Heat Transport in the Pacific

cross-equatorial heat transport may not be very evident in the cross equatorial transport plot in Figure 3.9 since it's computed for the Indopacific basin and not just the Pacific. In Figure 3.10, however, which shows OHT calculated manually through saved monthly output of meridional velocity times temperature (vT), we can see a clear and statistically significant (t-test, at the 99% confidence level, for the rolled averages) increase in the mean value of northward cross-equatorial ocean heat transport in the Pacific. The fact of decreasing downward heat flux in the North Pacific (it is dominated by the Kuroshio Extension region, Figure 3.11) despite a cooling of the region is unusual, and requires further analysis.

In the South Pacific (note that this region doesn't include the Pacific sector of the Southern Ocean, and the South Atlantic doesn't include the Atlantic Sector of the Southern Ocean either), there is net heat uptake throughout the time series, but heat content shows a consistent decrease, indicating that more heat is being transported to the Southern Ocean and across the equator. The reason for this heat uptake is more intuitive and is consistent with a general cooling of the surface as a result of the presence of additional mixing. The net effect of near-inertial waves averaged over 160 years appears to be moving from heat from the South Pacific into the North Pacific (where it is vented to the atmosphere primarily in the Kuroshio Extension Region),Southern Ocean, or Indian Ocean, which means that near-inertial waves do play an important role in the climate beyond simply changing the boundary layer depth, even though these changes are not large enough to be reflected in the peak OHT or meridional overturning circulation.

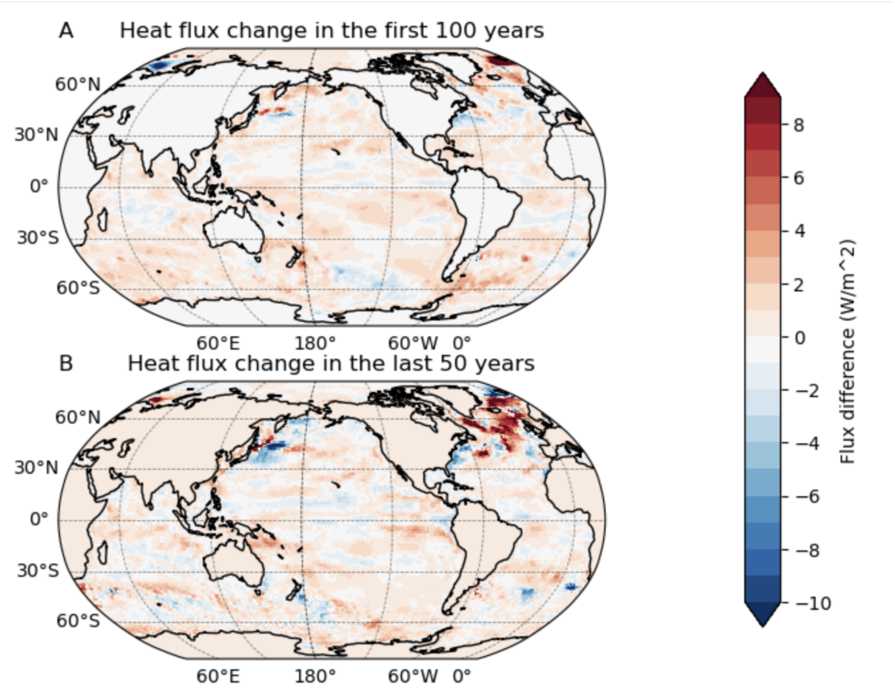


Figure 3.11: Heat flux difference at different sections of the time series

In the Atlantic, the opposite trends are observed. Further discussion of this basin is reserved for another time, as the focus of this thesis is on the more tractable Pacific Ocean. However, an increase in heat uptake by the North Atlantic is observed, similar to Jochum et al 2012, though later in the timeseries, and this increase in heat uptake appears to be driving the an increase in heat content, rather than inter-basin heat transfer, which is contrary to our expectations. The cause of this increased heat uptake in the Atlantic is not apparent. In the Southern Ocean, a consistent positive trend in surface heat flux is observed (Figure 3.10), meaning that the Southern ocean's rate of heat uptake is continuously increasing, which could have large impacts on global climate in the future.

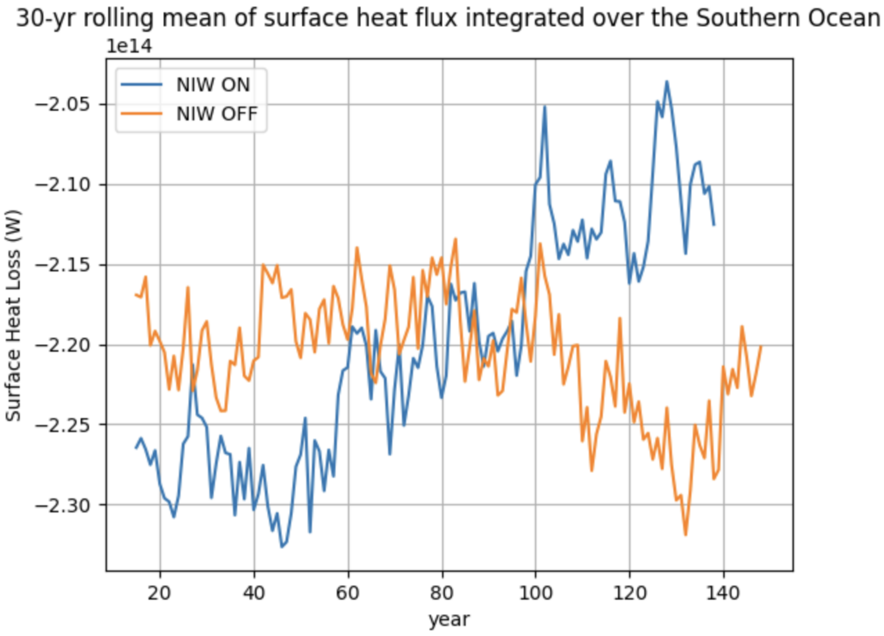


Figure 3.12: Surface downward heat flux integrated over the Southern Ocean

Chapter 4

Outlook

We observed that the addition of near-inertial wave energy to the system did not significantly impact peak ocean heat transport, mixed layer depth, or precipitation patterns. This confirms that the inclusion of near-inertial waves to studies on the effects of tropical cyclones on ocean heat transport would not significantly impact the results, which from realistic tropical-cyclone resolving simulations show only a couple of percentage points of change, similar to that observed with the inertial-waves simulation. However, near-inertial wave energy is able to penetrate quite deep (nearly 60% crosses the 600 m mark) and this results in significant heating deeper in the ocean, a result that hasn't been discussed (to our knowledge) in previous studies of either the impacts of storms on oceans or of the effects of near-inertial waves on climate. As these depths interact with the atmosphere on much longer timescales, near-inertial waves effectively serve to increase the memory of the ocean, and enable greater ocean heat uptake. The increase in ocean heat content in the upper 1000 m is equal to 8% of the heat taken up by the global ocean since the pre-industrial ages due to global warming. As the time series is only 150 years long, it remains to be seen what effects this stored heat could have on centennial timescales, and whether the pumping of heat to these deeper depths continues.

An transfer of internal wave energy from higher temperatures (¿ 21° C) to lower temperature classes (20-15° C) in the global mean is also observed, in the last fifty years of the timeseries accounting for 5-7% of the diffusive heat flux provided by background mixing across the 15 ° isotherm calculated by Holmes et al 2019(a). However, there are uncertainties in this estimate from the heat budget arising from the annual averages used for the budget calculation as well as the fact that the run with near-inertial waves turned on hasn't equilibrated fully yet. This analysis should be repeated with calculations being done online, and with the transport of internal heat content being determined for individual basins to further narrow down which pathways of global ocean heat transport are impacted by near-inertial waves.

Uncertainties in the representation of near-inertial waves in models remain, especially with regard to lateral propagation of the much more energetic lower modes and the eventual fate of this energy, the role of storm shape in driving effective near-inertial pumping, and the role of mesoscale features in increasing near-inertial energy transfer past the mixed layer. Future directions of this work include working out how to account for these factors. Near inertial waves also drive large-scale rearrangement of heat content between the ocean basins, and to determine what eventual effects the trends have (such as increasing cross equatorial heat transport and intermediate-depth heat storage in the Pacific, increasing heat uptake in the Atlantic and Southern Ocean, a longer timeseries would be required.

Climate change is also expected to change the intensity of midlatitude storms and tropical cyclones (Chemke et al, 2022), increasing near-inertial forcing and making it crucial to understand exactly how these waves affect how heat is distributed in the ocean, to better predict where heat will be taken up and stored in a warming climate. For this, it would be interesting to allow the surface forcing function for near-inertial waves to evolve with the climate state in a longer increased-CO2 run, and that is the next step for this project. To summarise, the questions raised by this project include:

- What are the impacts of the heat stored at intermediate depths by near inertial waves on the climate? At what time-scales do these impacts occur?
- How do we expect the strenghtening of near-inertial wave forcing in a climate change scenario to modify our current estimates of ocean heat uptake, as well as ocean heat transport?
- How can we better constrain the role of these waves in global ocean heat transport with the help of heat functions?

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