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Development of a regional ocean model for the Caribbean, including 3D dynamics, thermodynamics and full surface flux forcing

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Abstract

A regional ocean model based on the NEMO framework was developed for the Caribbean. The model includes tides, lateral boundary forcing from a global simulation, realistic thermodynamics and baroclinic dynamics, and atmospheric forcing from the ECMWF ERA5 reanalysis. A simulation of the year 2010 (with spin-up over 2009) was performed and the model was validated against sea-level observations from tide gauges and sea surface temperature observations from satellite. Typical temporal RMS error in sea-level is 6-8 cm and spatial RMS error in time-mean SST is 0.53 degC, with a mean offset of 0.08 degC but with localised regional extremes of up to +/- 3 deg C. Hurricanes Igor and Tomas show only a weak signature, with less than 20 cm storm surge, in both the tide gauge observations and model data for the three sites examined in the eastern Caribbean. Greater sea-level impacts experienced from these hurricanes are likely to have been due to high-frequency surface wind-waves and swell, which are not present in the tide gauge observations and are not simulated, nor parameterised, in this version of the model. These processes should be considered in addition. Further impacts may have not been directly related to sea level, e.g. landslides due to heavy rainfall and winds.

Note:

This project involved a significant amount of model development and time spent overcoming technical challenges (see Appendix), which somewhat limited the time available for validation and application. The final, functioning model code is available from a GitHub release on Zenodo (Wilson, Harle and Wakelin, 2019; http://doi.org/10.5281/zenodo.3228088), complete with software to download and set up the model and boundary forcing, tailored for simulation on the ARCHER national supercomputer in the UK.

1. Introduction

The primary aim of this project was to adapt an existing regional configuration of the NEMO modelling framework for the Caribbean, used for tide-surge modelling (the NEMO-surge code base), into a configuration to include surface forcing of heat and freshwater and active thermodynamics able to affect temperature, salinity and density evolution. The 2009 initial conditions and the 2009-2010 lateral boundary conditions for the Caribbean domain were provided by an existing global simulation of NEMO (ORCA0083_N006), which does not include tides. This report details the main steps in developing the model, including the boundary forcing.

The secondary aim was to validate the model against observations. The year 2010 was chosen as a focus, because it included Hurricanes Igor (8 - 21 September) and Tomas (29 October - 7 November), which were particularly destructive in the eastern Caribbean.

2. NEMO framework

The Nucleus for European Modelling of the Ocean (NEMO) framework is a state-of-the-art modelling framework for research activities and forecasting services in ocean and climate sciences, developed by a European consortium (www.nemo-ocean.eu). Further details on the model may also be found in its user guide (https://doi.org/10.5281/zenodo.1464816). NEMO is used in many national centres across Europe and is the main type of ocean model used in the UK at the National Oceanography Centre and at the Met Office.

2a. ORCA global reference simulation

NEMO version 3.6 was used for the existing ORCA0083-N006 global reference simulation at NOC, with nominal 1/12° resolution, 75 vertical z-levels, with bottom topography (ETOPO2) represented as partial steps. The model was forced with the Drakkar Surface Forcing dataset version 5.2 and run initially from 1958-2012, with an extension to 2015. More details of this simulation may be found in Madec, 2008; Marzocchi et al., 2015; Moat et al., 2016.

2b. Benefits of a regional model

The global simulation ORCA0083-N006 has a massive computational expense and is relatively slow to run, even on the ARCHER national supercomputing facility. A regional subdomain requires less computation, simply because it typically has fewer gridcells than the global model. The lower computational demands of a regional model allow broader exploration of choices of forcing datasets and physical parameters which would not be practical in a global configuration.

2c. A regional model of the Caribbean

For this application to the Caribbean, tidal forcing (not present in the global model) was added. The surface fluxes of buoyancy (due to heat and freshwater fluxes) and momentum (due to wind and sea-level pressure) were taken from a recent reanalysis dataset, ECMWF ERA5 (C3S, 2017).

Initially, an existing model of the Caribbean, using the NEMO-surge code base, was used and adapted. This model had been previously configured for tide-surge modelling, without active thermodynamics affecting the density stratification. As such, it was not set up to use surface flux forcing of buoyancy, but only of momentum. Also, its thermodynamic equation of state was not active. Although the initial plan was to adapt this code to make it work in a more general setting, it was later decided to change to an alternative code base that was already set up as a general 3D baroclinic model with active thermodynamics. Instead, this model would be adapted to the Caribbean domain and would have other changes to its physics appropriate to the application in this region, e.g. a hybrid sigma-z-partial-step vertical coordinate, which better captures the sharp transition from open ocean to shelf bathymetry, leading to improved dynamical interaction with the topography.

Model parameters, including timestep, diffusivity of momentum and tracers, choice of advection scheme, vertical mixing scheme and choice of surface bulk parameterisation, were optimised (**Table 1**), based on expert advice and the numerical stability of the model.

Domain size:	-4.91°N to -31.56°N, 100.17°E to 54.92°E
Horizontal resolution:	1/12° lat-lon
Vertical resolution:	75 hybrid sigma-z-partial-step levels
bathymetry:	GEBCO 2014 (30-arc-second)
timestep:	240 seconds
Advection:	Total variance dissipation (FCT)
Vertical mixing:	GLS scheme, k-eps (Canuto A)
Vert mix bg val:	1e-7 m^2/s
Bottom friction:	Nonlinear (drag coefficient: 2.4e-3)
Lateral diff:	Bi-Laplacian
Horiz viscosity:	-1e9 m^4s^{-1}
NEMO version:	4 (pre-release)
model size:	544 x 342 x 75 cells
processors:	192 = 168 + 24
Surface forcings:	ECMWF ERA5 reanalysis, NCAR bulk param.
Tidal forcing:	TPXO9
Lateral boundaries:	Global NEMO: ORCA0083-N006

Table 1: *Summary of the regional Caribbean NEMO model configuration.*

The Appendix lists some of the main steps in developing the model and the lessons learnt, with the aim of improving efficiency of future NEMO model development.

3. Model validation

This part of project mainly focussed on the eastern Caribbean and St. Vincent and the Grenadines in particular (sea level, tides and surges), but with some coverage of the whole Caribbean domain too (sea surface temperature and ocean currents).

3a. Sea level at tide gauges

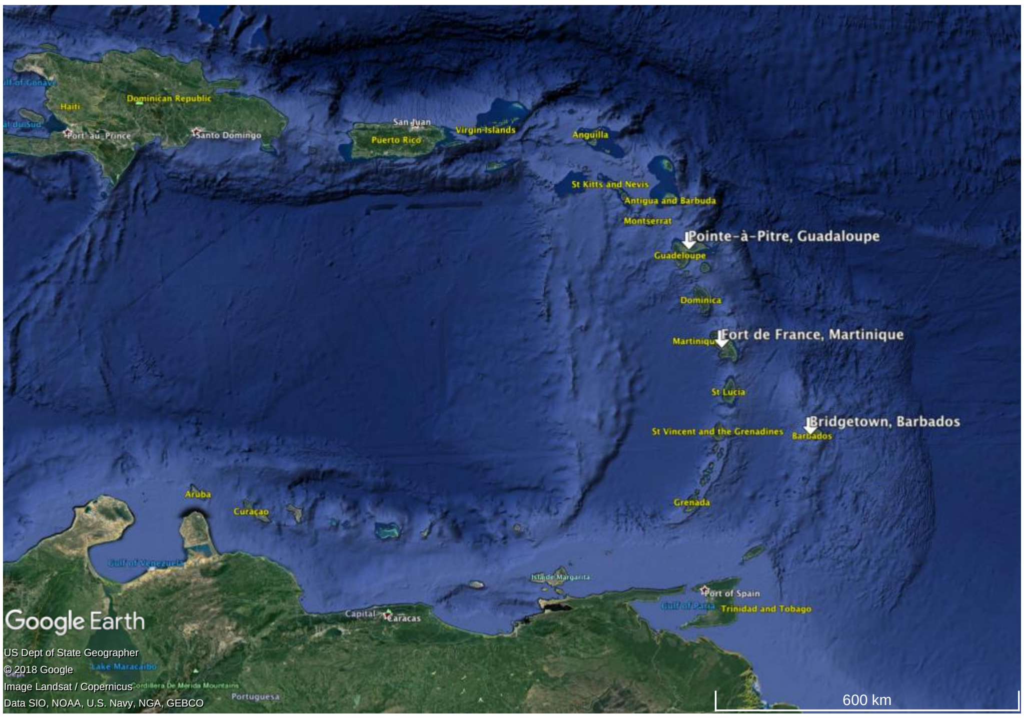


Figure 1. *Map of the eastern part of the domain, taken from Google Earth, showing the location of the three tide gauge sites used for sea-level validation (white arrows).*

The nearest, quality-controlled, hourly data to St. Vincent and the Grenadines, valid during 2010 was from three tide gauge sites, shown in Fig. 1:
i) Bridgetown, Barbados; ii) Pointe-à-Pitre, Guadaloupe; and iii) Fort de France, Martinique.

The tide gauge data came from the GESLA-2 database (https://gesla.org/) and is described in Woodworth et al. (2017).

Fig. 2 shows timeseries for 2010 of total sea-level at each of the three sites (blue) and data from the nearest NEMO model gridcell to each site (red). The root-mean-square error (RMSE) is 8.4 cm

(Bridgetown, Barbados), 6.2 cm (Fort de France, Martinique) and 7.1 cm (Pointe-à-Pitre, Guadaloupe). These errors are similar magnitude to the RMSE for the UK's operational tide-surge model, CS3X, when averaged across the 44 tide gauge sites around the UK Tide Gauge Network. Therefore, we can conclude that NEMO performs reasonably well in predicting total sea-level.

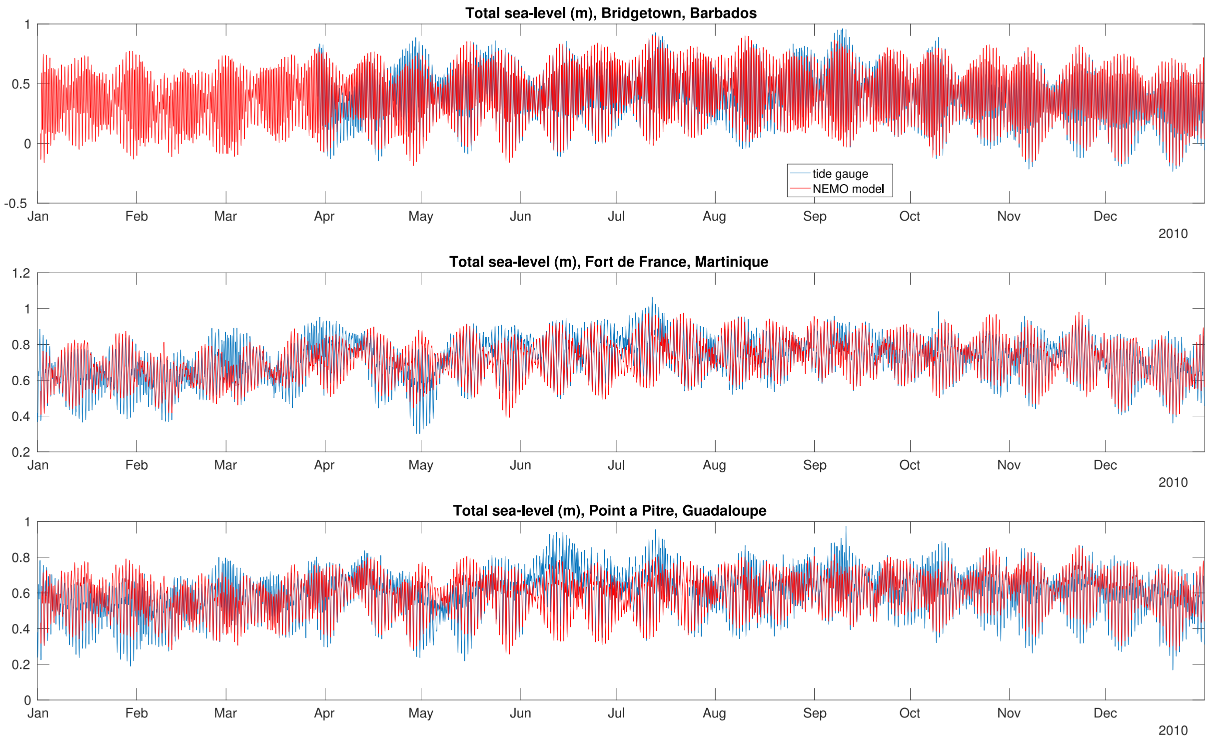


Figure 2. *Timeseries of total sea-level for 2010 at the three chosen sites, showing tide gauge observations (blue) from GESLA and data from the nearest NEMO model grid point (red). These timeseries include components from the tide, from atmosphere-forced components (storm surge, inverse barometer) and from ocean dynamics internal to the model (nonlinear currents) and from lateral boundary forcing from the global model (nonlinear currents, external storm surge). Note that high-frequency surface wind-wave effects and swell are not simulated in this version of the NEMO model and specialist wave models and wave observations need to be considered in combination for a more complete impacts study.*

However, the much smaller amplitude of tide-plus-surge in the Caribbean, compared to that of extensive shallow shelf seas such as for the UK, means that such errors make up a larger fraction of the total. If there was a practical need to predict tide-plus-surge at, say, approaching 1-2 cm accuracy, then further refinement of the NEMO model and the resolution of atmospheric forcing data might be advisable.

It is clear that the timeseries in Fig. 2 are dominated by the tidal signal, so a tidal analysis was performed to remove this from the total sea-level, to leave a non-tidal residual. The non-tidal residual is usually associated with storm surge, but it may also contain observation/model error and error associated with the tidal analysis, typically assumed to be small (< ~ few cm) - see Flowerdew et al. (2010) for a further discussion, with an example for a region with large tidal amplitude.

Table 2 shows the tidal constituents found from the harmonic analysis of observations and the NEMO model for Bridgetown, Barbados. There is a close match in amplitude and phase for the main constituents, with model and observations typically being within a few percent of each other. The order of largest amplitude constituents varies slightly, with 'M1' and 'M2' swapping position, but these are very similar in amplitude.

Observations (Bridgetown, Barbados)			NEMO model (Bridgetown, Barbados)		
Top 10 tidal constituents, sorted by amplitude	Amplitude (m)	Phase (deg)	Top 10 tidal constituents, sorted by amplitude	Amplitude (m)	Phase (deg)
'2N2'	0.2356	221.75	'2N2'	0.2395	207.58
'M1'	0.0825	236.68	'M2'	0.0858	232.05
'M2'	0.0796	248.06	'M1'	0.0822	223.98
'MF'	0.0698	228.58	'MF'	0.0697	220.49
'OO1'	0.0518	208.77	'OO1'	0.0506	188.67
'O1'	0.0272	236.91	'O1'	0.0273	224.71
'LAM2'	0.0204	242.83	'LAM2'	0.0226	232.38
'MM'	0.0130	227.07	'MM'	0.0140	207.19
'OQ2'	0.0106	208.33	'MP1'	0.0046	152.43
'SO1'	0.0085	172.70	'MSN6'	0.0043	351.35

Table 2: *Main tidal constituents, their amplitude and phase, from tidal analysis of GESLA tide gauge observations and NEMO model data for 2010 at Bridgetown, Barbados. Constituents have been sorted by amplitude, with small values, less than 0.01 m, shaded grey.*

Similarly, Table 3 makes the same comparison for Fort de France, Martinique. Here, the tidal regime is weaker than in Bridgetown, with largest amplitude being 8.3 cm compared to 24 cm. Again, amplitudes and phases are typically within a few percent of each other. Exceptions come from small amplitude constituents, such as 'M2', where the observations are ~ 1 cm amplitude, but the model's 'M2' is not shown, so may be considered to be below the 1 cm noise threshold.

Observations (Fort de France, Martinique)			NEMO model (Fort de France, Martinique)		
Top 10 tidal constituents, sorted by amplitude	Amplitude (m)	Phase (deg)	Top 10 tidal constituents, sorted by amplitude	Amplitude (m)	Phase (deg)
'M1'	0.0831	238.53	'M1'	0.0857	226.56
'MF'	0.0628	228.47	'MF'	0.0628	224.08
'2N2'	0.0587	208.58	'2N2'	0.0346	197.95
'O1'	0.0252	237.94	'O1'	0.0284	226.75
'OO1'	0.0167	179.84	'OO1'	0.0134	158.05
'M2'	0.0147	238.18	'MM'	0.0108	213.51
'MM'	0.0103	228.56	'M3'	0.0084	278.84
'S1'	0.0060	232.70	'MK3'	0.0064	313.10
'OP2'	0.0045	214.82	'M2'	0.0061	234.71
'SIG1'	0.0044	221.05	'MNS2'	0.0055	299.28

Table 3: *Main tidal constituents, their amplitude and phase, from tidal analysis of GESLA tide gauge observations and NEMO model data for 2010 at Fort de France, Martinique. Constituents have been sorted by amplitude, with small values, less than 0.01 m, shaded grey.*

Finally, Table 4 shows the equivalent for Pointe-à-Pitre, Guadaloupe. Like Fort de France, Martinique, the tidal regime here is weak. The two largest tidal constituents, '2N2' and 'M1' are 9.2

cm and 7.5 cm from observations, and 6.9 cm and 7.5 cm from the model, respectively. The error of 2.3 cm in '2N2' is probably at the limit of accuracy of the harmonic analysis and observational error, so although this is a large fraction, it may not be possible to reduce such error in such a weak tidal regime. Phase errors of ~15-20 degrees represent about 4-6 % of a wavelength.

Observations (Pointe-à-Pitre, Guadaloupe)			NEMO model (Pointe-à-Pitre, Guadaloupe)		
Top 10 tidal constituents, sorted by amplitude	Amplitude (m)	Phase (deg)	Top 10 tidal constituents, sorted by amplitude	Amplitude (m)	Phase (deg)
'2N2'	0.0922	233.40	'M1'	0.0745	219.93
'M1'	0.0750	234.39	'2N2'	0.0694	210.52
'MF'	0.0600	228.18	'MF'	0.0642	217.97
'M2'	0.0364	249.45	'M2'	0.0347	233.37
'O1'	0.0230	236.50	'O1'	0.0246	222.36
'OO1'	0.0218	221.33	'OO1'	0.0151	189.57
'MM'	0.0118	224.72	'MM'	0.0129	204.87
'LAM2'	0.0094	254.18	'LAM2'	0.0087	233.09
'OQ2'	0.0055	233.76	'MP1'	0.0034	150.03
'SO1'	0.0049	158.55	'MSN6'	0.0032	150.07

Table 4: *Main tidal constituents, their amplitude and phase, from tidal analysis of GESLA tide gauge observations and NEMO model data for 2010 at Pointe-à-Pitre, Guadaloupe. Constituents have been sorted by amplitude, with small values, less than 0.01 m, shaded grey.*

Overall, the performance of the tidal dynamics in the NEMO model are acceptable, compared to tide gauge observations, so we may use the harmonic tidal analysis to remove the tidal signal from the total sea-level timeseries in Fig. 2 and examine the non-tidal residual - Fig. 3. The additional caveat here is that the error associated with observational error and error in tidal analysis (the latter applying to both the observations and the model), is probably a few cm for this residual.

Fig. 3 shows that for both observations (blue) and model (red), the non-tidal residual does not exceed approximately +/- 20 cm over the whole of 2010. This suggests that at these three sites, storm surges (as formally defined) are relatively small, despite periods of intense hurricane forcing. The typical 6-8 cm RMS error between model and observations somewhat obscures the detailed picture in Fig. 3, that there is generally good correlation on long timescales, approaching annual, but that on timescales of days to weeks, the correlation may be intermittently either good or poor. This might reflect a source of error with random phase.

However, it was not the aim of the project to produce a model applicable for operational storm surge forecasting and it is surprising that this early iteration performs as well as it does, without further tuning or higher resolution atmospheric forcing, e.g. from a weather forecast-reanalysis system. In terms of the basic validation of this regional model, Fig. 3 suggests that the model does a reasonably good job of simulating the ocean's response to atmospheric forcing.

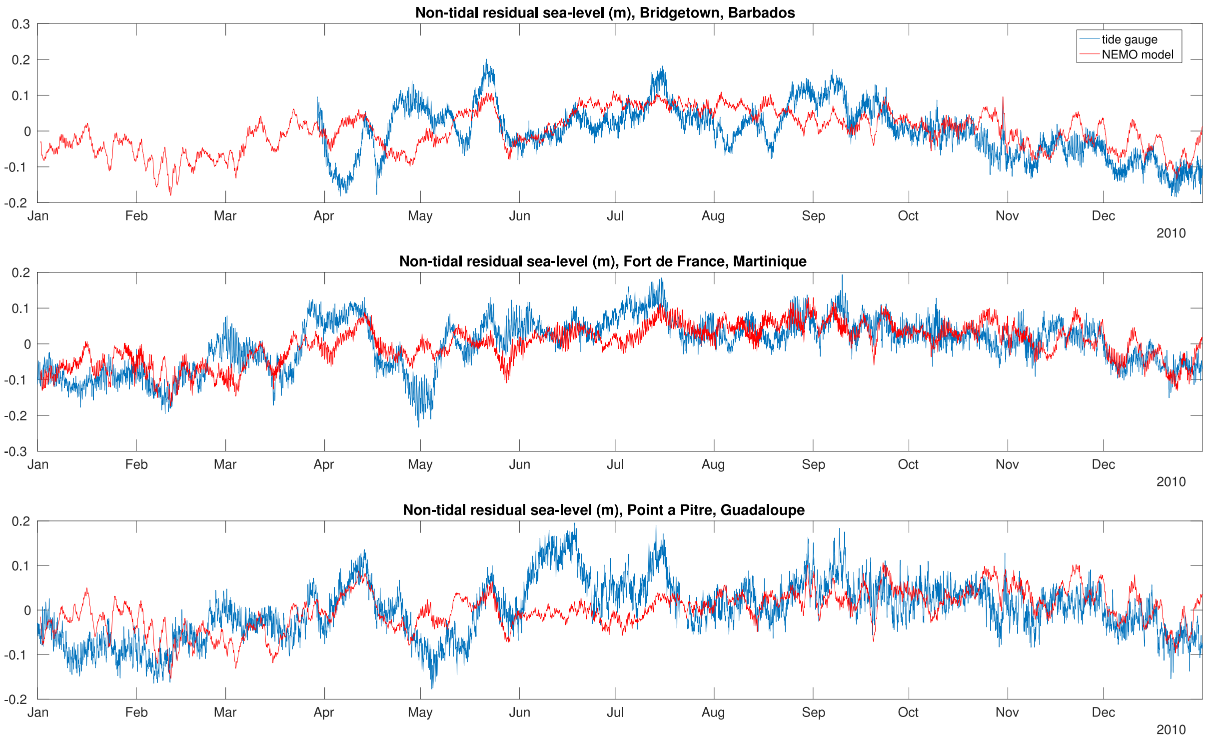


Figure 3. *Timeseries of non-tidal-residual sea-level for 2010 at the three chosen sites, showing tide gauge observations (blue) from GESLA and data from the nearest NEMO model grid point (red). Tide gauge observations for Bridgetown were not available before late March.*

Taking a closer look at particular Hurricane events during 2010, the periods around Hurricane Igor (Fig. 3) and Hurricane Tomas (Fig. 4) are shown for the three sites.

"Hurricane Igor was the most destructive tropical cyclone on record to strike the Canadian island of Newfoundland, and the strongest hurricane of the 2010 Atlantic hurricane season. Igor originated from a broad area of low pressure that moved off the Cape Verde islands on the west coast of Africa on September 6, 2010. Tracking slowly westward, it developed into a tropical depression on September 8 and strengthened into a tropical storm shortly thereafter. Higher wind shear temporarily halted intensification over the following days. On September 12, explosive intensification took place, and Igor reached Category 4 status on the Saffir–Simpson Hurricane Wind Scale. By this time, Igor had already begun a prolonged turn around the western periphery of the subtropical ridge. Peaking with winds of 155 mph (250 km/h), the cyclone began to enter an area unfavorable for continued strengthening, and Igor gradually weakened before brushing Bermuda as a minimal hurricane on September 20. After turning northeastward, the system began an extratropical transition, which it completed shortly after striking southern Newfoundland. The remnants of Igor were later absorbed by another extratropical cyclone over the Labrador Sea on September 23." (Wikipedia: https://en.wikipedia.org/wiki/Hurricane_Igor)

The closest approach of Hurricane Igor to the Lesser Antilles was during 14-18 September (https://www.nhc.noaa.gov/data/tcr/AL112010_Igor.pdf).
Fig. 4 shows that the surge in both observations and model was comparatively small during this period at each of the three sites. The largest surge appears to be at Pointe-à-Pitre, Guadaloupe, during

7-11 September, although it is less than 20 cm in the tide gauge observations. The model does not capture this event well, however.

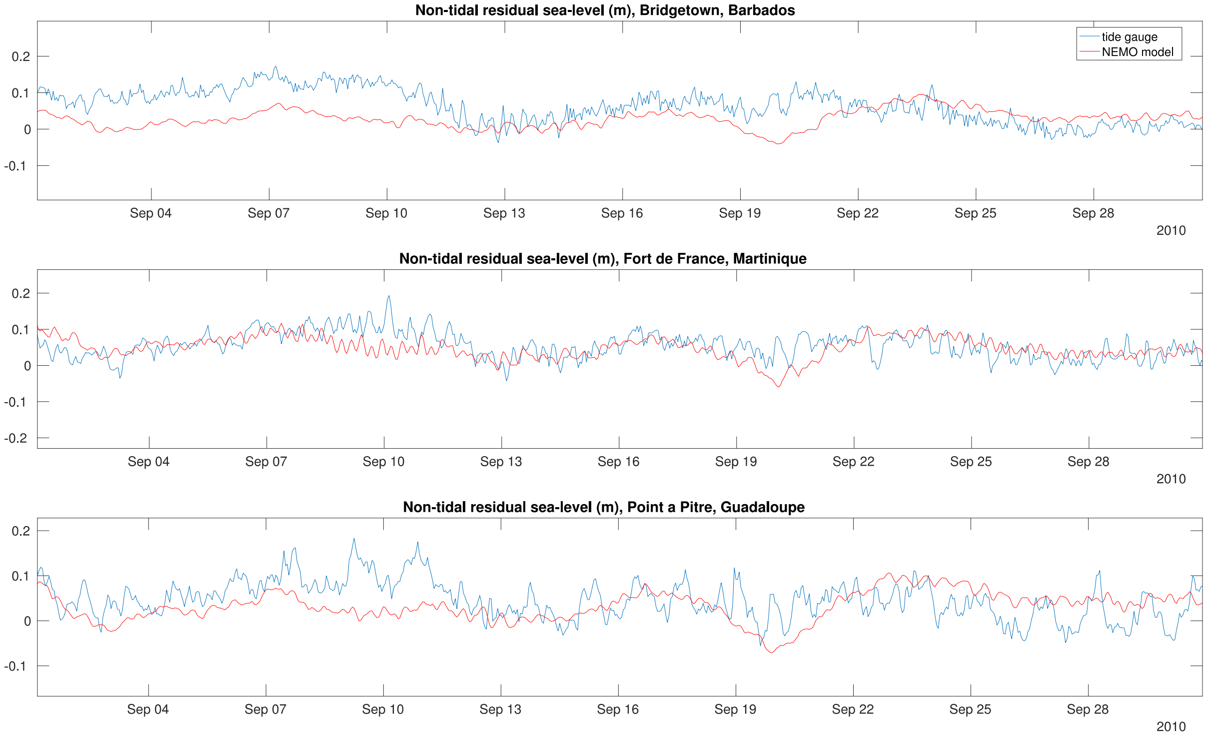


Figure 4. *Timeseries of non-tidal-residual sea-level for the period covering the passage of Hurricane Igor at the three chosen sites, showing tide gauge observations (blue) from GESLA and data from the nearest NEMO model grid point (red). Note that neither the tide gauges nor the model indicate values in excess of 0.2 m for these locations.*

"Hurricane Tomas was the latest recorded tropical cyclone on a calendar year to strike the Windward Islands. The nineteenth named storm and twelfth hurricane of the 2010 Atlantic hurricane season, Tomas developed from a tropical wave east of the Windward Islands on October 29. Quickly intensifying into a hurricane, it moved through the Windward Islands and passed over Saint Lucia. After reaching Category 2 status on the Saffir-Simpson scale, Tomas quickly weakened to a tropical storm in the central Caribbean Sea, due to strong wind shear and dry air. Tomas later regained hurricane status as it reorganized near the Windward passage.

Throughout the hurricane's path, 71 people are known to have been killed, 14 of whom were in Saint Lucia. In the wake of the storm in Haiti, flooding intensified a cholera outbreak indirectly causing more fatalities. However, direct impacts from the hurricane in Haiti were less than anticipated." (Wikipedia: https://en.wikipedia.org/wiki/Hurricane_Igor)

Hurricane Tomas passed over Barbados and St. Vincent during 30 October (https://www.nhc.noaa.gov/data/tcr/AL212010_Tomas.pdf). In Fig. 5, this event is apparent at Bridgetown, Barbados, in both the tide gauge observations and NEMO model, where the correlation is strikingly accurate for the growth phase of the storm surge, but the model decays more slowly. In both cases, the storm surge does not exceed 10 cm here. Further north, at Fort de France, Martinique, there does not appear to be anything significant in terms of storm surge. However, yet further north, at Pointe-à-Pitre, Guadaloupe, the tide gauge observations show a peak surge of around 12 cm on 31 Oct. The model does not capture this sharp peak as well, possibly due to the challenge of representing the complex coastal bathymetry in the region for this model grid resolution.

Figure 5. *Timeseries of non-tidal-residual sea-level for the period covering the passage of Hurricane Tomas at the three chosen sites, showing tide gauge observations (blue) from GESLA and data from the nearest NEMO model grid point (red). Note that neither the tide gauges nor the model indicate values in excess of 0.12 m for these locations, but that there is a signal apparent at the end of October in both Bridgetown and Pointe-à-Pitre.*

3b. Satellite observations of sea surface temperature

The model was compared against Advanced Very High Resolution Radiometer (AVHRR) observations of sea surface temperature (SST) (Kilpatrick et al., 2001), provided by the NERC Earth Observation Data Acquisition and Analysis Service (NEODAAS). The time-mean of the SST was calculated for 2010. NEMO model time-mean SST is shown in Fig. 6 and AVHRR SST observations are shown in Fig. 7, plotted on the same colour scale.

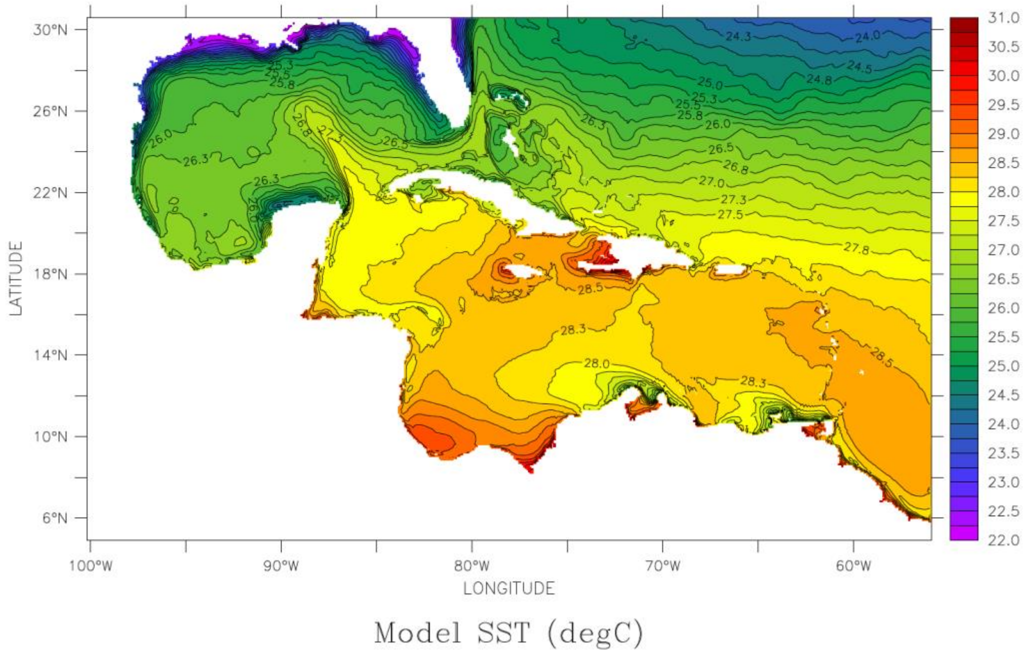


Figure 6. *Time-mean of sea surface temperature (SST) for 2010 from the NEMO model. Land is shown in white. The Panama Basin is not included in the simulation.*

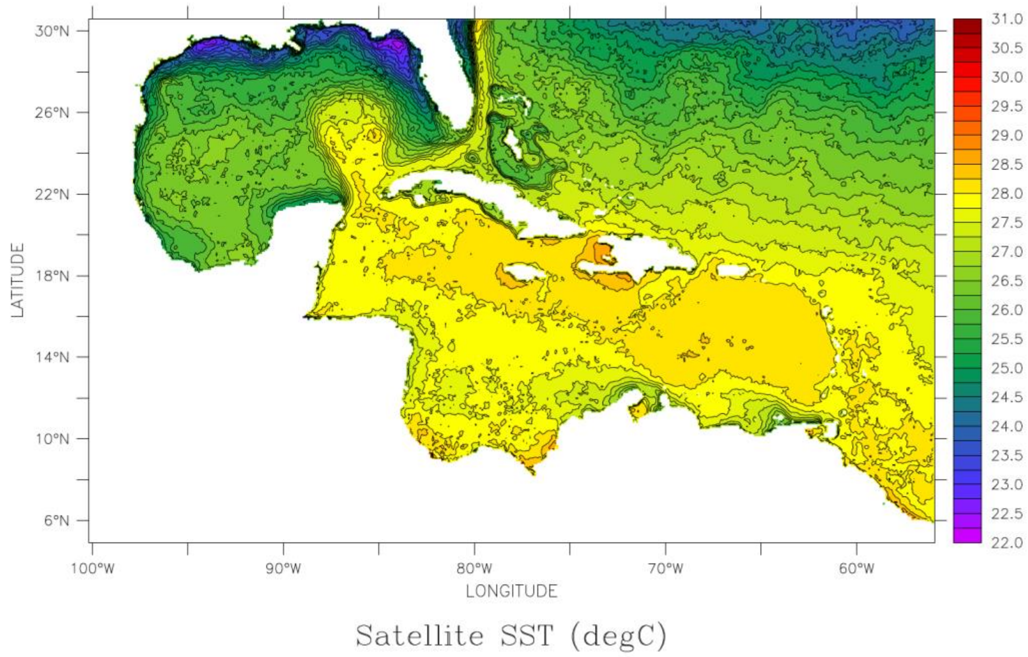


Figure 7. *Time-mean of sea surface temperature (SST) for 2010 from AVHRR satellite observations.*

Averaged over the spatial domain, model SST is 26.93 degC and satellite SST is 26.85 degC. It is encouraging that these means agree to within only 0.08 degC, however, there are some larger misfits, as can be seen in Fig. 8. The standard deviation of these model-observation differences over the spatial domain is 0.53 degC, but there are further regional characteristics. The northern half of the model domain is typically colder than observations and the southern half is typically warmer, by about +/- 1 degC, but with localised extrema of up to +/- 3 degC. There is the added complication of comparing satellite SST, which is a 'skin' temperature, with a model that has a varying top grid box depth (e.g. in shallow waters during summer it's likely to be warmer and the thicker grid cells cooler).

The larger of the errors seem to reside in shallow, near-coastal regions, or are associated with the loop current in the Gulf of Mexico. Improvements in the near-coastal regions might be found by tuning either the form of the bulk parameterisation of surface fluxes or the mixed layer physics, as these shallow regions are more sensitive than the deep, open ocean. Some error associated with the loop current may be related to the internal, chaotic variability in the system and that the eddy-resolving NEMO model is sensitively dependent on initial and boundary conditions - i.e. a small change in either may lead to a substantial change to the loop current over long timescales. Ensemble experiments may be used to examine this hypothesis, but this was beyond the scope of the current project.

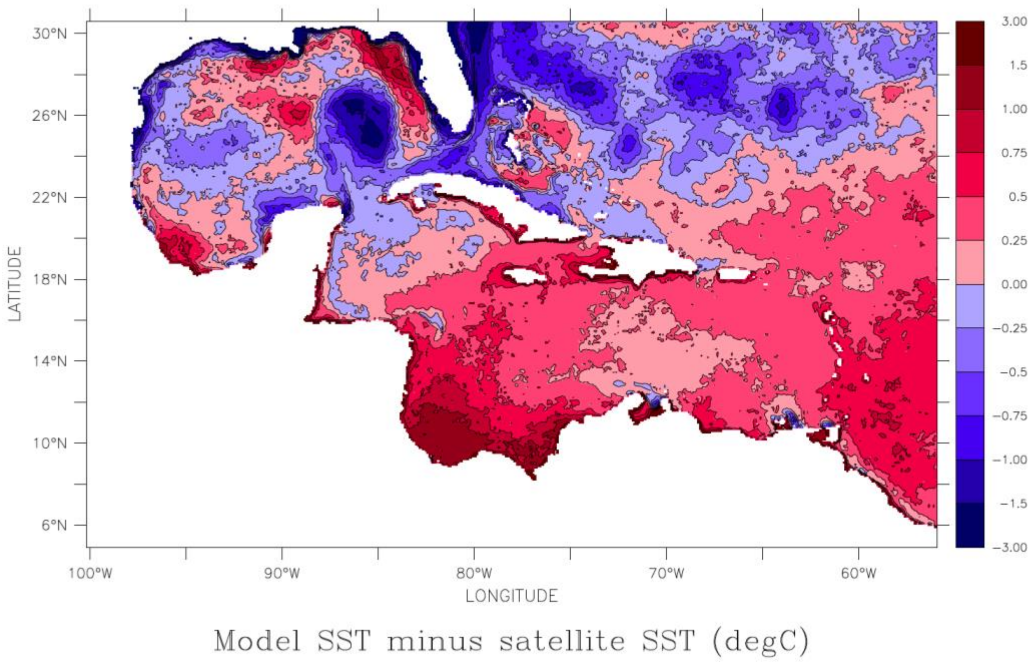


Figure 8. *Difference showing model-minus-observations for the time-mean of SST over 2010. Note that the colour scale is non-uniform.*

As well as examining the spatial map of time-mean SST, the seasonal cycle of the domain-mean SST was analysed over 2010. Fig. 9 shows this timeseries for the NEMO model (black) and AVHRR observations (red). The model is too cold during Jan-Feb and too warm during May-August. The deviation is typically less that 1 degC during these periods and far less at other times. Note that the model timeseries is hourly and that it is possible to see the diurnal cycle of solar heating. The satellite observations are daily, so the diurnal cycle is averaged out.

Further work to improve the performance of the model might focus on the choice of bulk parameterisation used in NEMO (the NCAR algorithm (Large and Yeager, 2008) was used here). Some other options available in NEMO are COARE 3.0, COARE 3.5 and ECMWF. Brodeau et al. (2017) examine the effect of various choices.

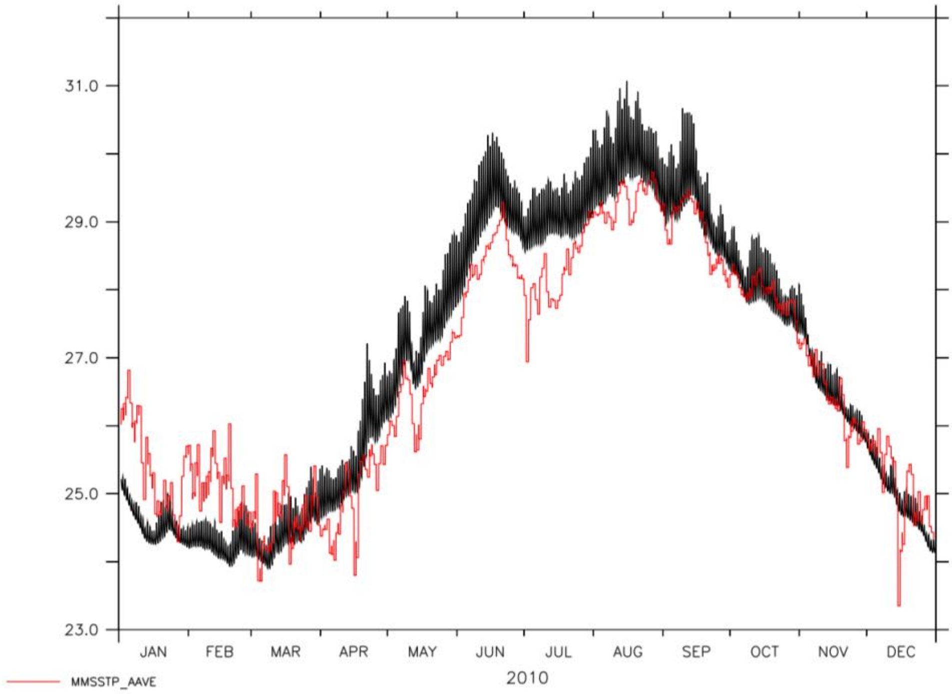


Figure 9. *Annual cycle of domain-mean SST (degC) for 2010. AVHRR satellite observations are shown in red. NEMO model is shown in black.*

3c. Ocean currents

Fig. 10 shows the time-mean surface currents from NEMO, averaged over 2010. These are broadly similar to the surface geostrophic currents from satellite altimetry shown in Fig. 1a of Alvera-Azcárate et al. (2009), where their long-term mean covers Oct. 1992 - Feb. 2006.

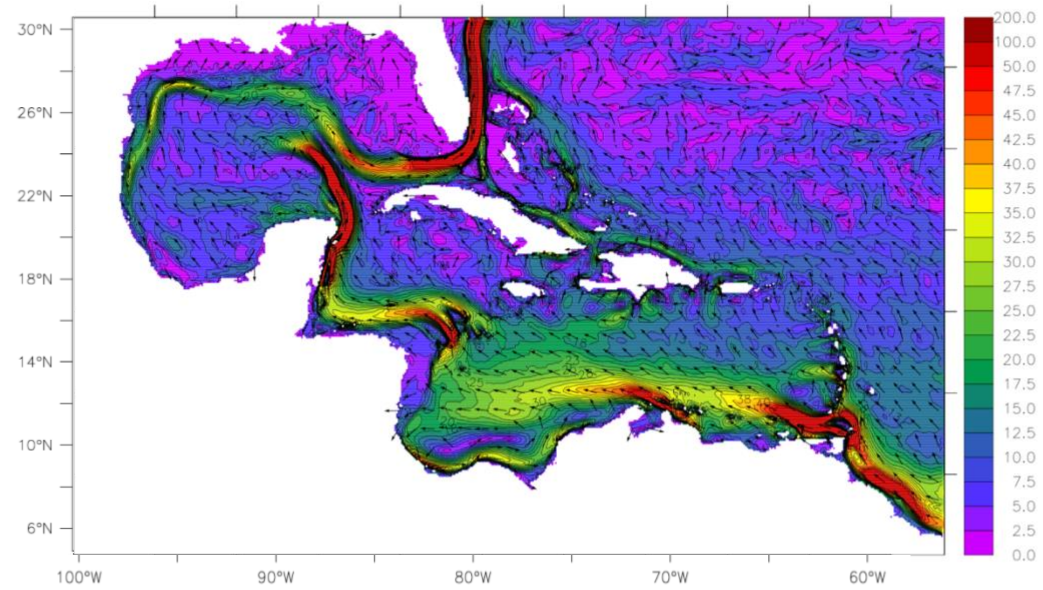
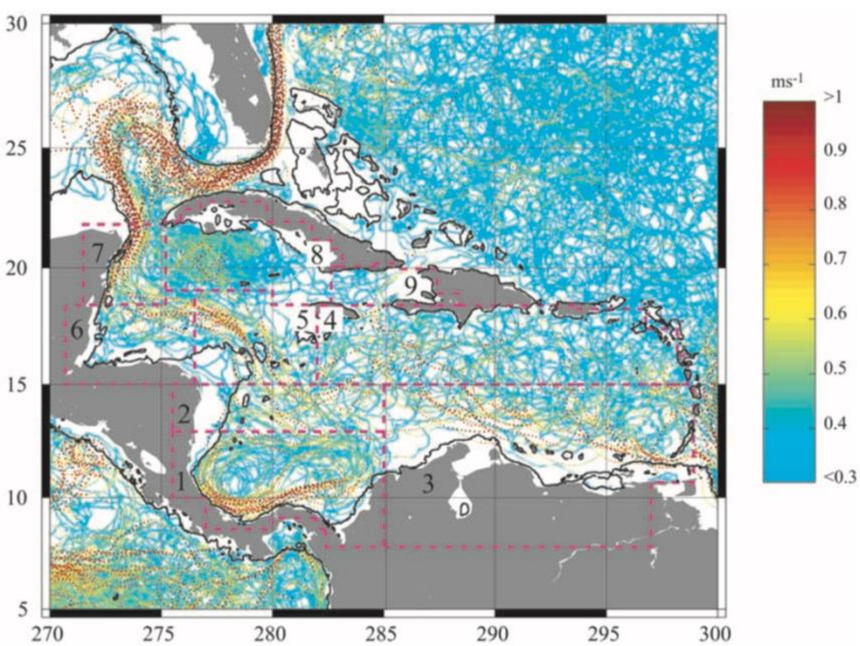


Figure 10. *Time-mean surface currents from the NEMO model for 2010. Current speed (cm/s) is shaded. Vectors of unit magnitude show current direction only. Note the non-uniform contour scale.*

Centurioni and Niiler (2003) examine the time-mean surface currents from surface drifters over 1996-2001. They produce a map of current speed (Fig. 11), that shows very similar structure to the 2010 time-mean from NEMO.

Figure 11. *From Centuroni and Niiler (2003). Trajectory of drifters. 302,064 positions are shown, 57,585 of which are inside the dashed boxes. Each position is color-coded in accordance with the computed speed. The thick black line is the 200 m depth contour.*



Further comparison with estimates in Centuroni and Niiler (2003) show that the 2010 time-mean surface currents match climatological speed and direction very well, except perhaps in the details of the loop current in the Gulf of Mexico. Again, these differences may be due to internal variability.

Finally, the barotropic (i.e. depth-mean) currents for the 2010 time-mean were also diagnosed. Fig. 12 shows that these currents are quite different from the surface currents, being typically a factor of 10 weaker, reflecting the fact that the strongest currents are typically at the surface, with much weaker currents at depth.

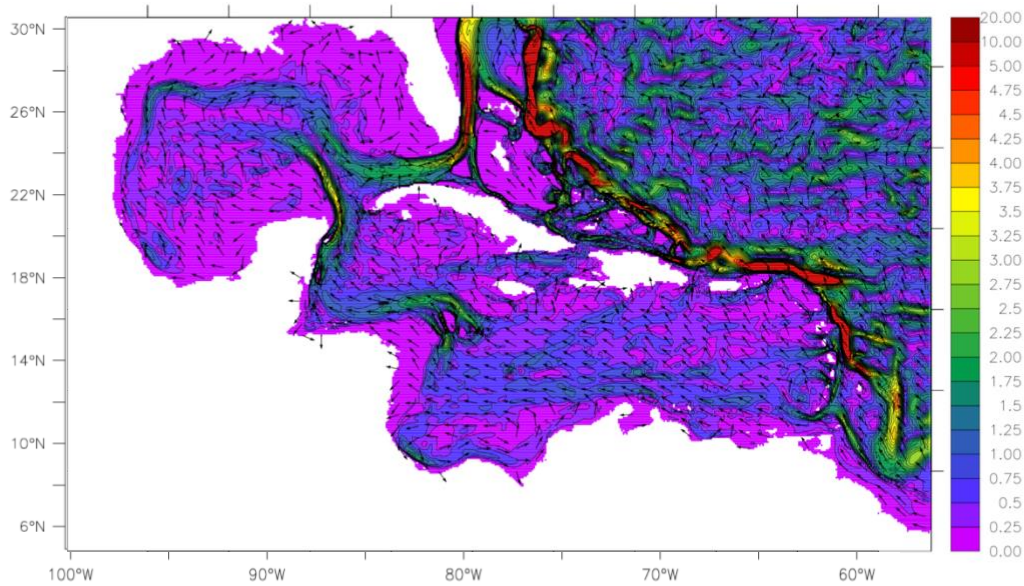


Figure 12. *Time-mean barotropic (depth-mean) currents from the NEMO model for 2010. Current speed (cm/s) is shaded. Vectors of unit magnitude show current direction only. Note the non-uniform contour scale, which is a factor of 10 weaker than in Fig. 10.*

The dominant barotropic currents are the Antilles Current, flowing northwestwards at up to 20 cm/s, and the Gulf Stream, also reaching 20 cm/s in the depth-mean. Also evident are multiple, quasi-zonal jet structures, of a few cm/s, in the subtropical gyre.

These structures have only recently been found in observations and eddy-resolving ocean models (e.g. Maximenko et al., 2005).

4. Main conclusions

This regional configuration of NEMO is a basis for future modelling in the Caribbean. It does an acceptable job of simulating the tide and surge components of sea-level, as well as SST and ocean currents. Further improvements to the model may come from choice of surface flux bulk parameterisation, which is easily adjusted in the code, or from tuning of the mixed layer scheme or vertical mixing, which are somewhat more involved. Also, for improved simulation of regional sea level and currents, ensemble experiments may be informative for exploring internal, chaotic variability. Finally, the main scientific conclusion from this study is that storm surges for the three sites in the eastern Caribbean during 2010 are weak (less than 20 cm), even during hurricane events. A hypothesis for why storm surges are weaker here than, say over the UK shelf seas during winter, is that Barbados, Martinique and Guadaloupe do not have extensive regions of shallow shelf on the scale of coastally-trapped waves (~ Rossby deformation radius) or larger, so the generation of storm surges is much more limited. Instead, high-frequency surface wind-waves and swell, which are not present in the tide gauge observations and are not simulated, nor parameterised, in this version of the model, are more likely to be associated with significant impacts related to hurricanes, as are other effects due to intense wind, rain, landslides, etc. Surface wind-waves are often several metres in significant wave height and therefore dominate storm surges of a few tens of centimetres. These effects may be additive to a certain degree, but their potential nonlinear interaction would require a further modelling study.

Although observed and modelled tide and surge are weak here, there is scope for improving agreement between model and observations. For example, even a high lateral resolution of 1/12 deg. does not fully capture complex coastline bathymetry, which is probably of some relevance for embayments such as Pointe-à-Pitre. If further model refinement was required for the Windward Islands, future development of this model configuration might involve increasing the lateral resolution or introducing nested models (e.g. via AGRIF). Additionally, the location of the eastern boundary might be extended further east to permit more tide-surge response to develop, and the temporal resolution of the external lateral boundary forcing might also be increased.

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Tidal forcing came from TPXO9 (http://volkov.oce.orst.edu/tides/global.html; Egbert and Erofeeva, 2002). The atmospheric forcing (ERA5) was generated using Copernicus Climate Change Service Information [accessed 2018]. We acknowledge the Nucleus for European Modelling of the Ocean (NEMO) consortium (www.nemo-ocean.eu) for the modelling framework used in this study. This work used the ARCHER UK National Supercomputing Service (http://www.archer.ac.uk) and also JASMIN, the UK's collaborative data analysis environment (http://jasmin.ac.uk). This work forms part of the Commonwealth Marine Economies programme, which is funded by the UK government's Commonwealth Sustainability Fund, part of the Conflict, Stability and Security Fund (CSSF).

Appendix: Development steps, technical challenges and lessons learnt (LL)

A sketch of the main steps is shown below, with comments on the technical challenges and lessons learnt, where appropriate. The detailed recipe for achieving each step is typically lengthy and regularly evolving, so is not shown here. The recipes are available on the (private) NOC-MSM Github repository. To access this repository, please contact Jeff Polton (jelt@noc.ac.uk).

A1. Define the domain: model grid and dimensions

Could use these instructions to generate the grid coordinates.
https://github.com/NOC-MSM/NEMO_cfgs/blob/master/recipes/docs/source/build_and_create_coordinates.rst

However, the coordinates.nc file was copied from the existing Caribbean domain setup made by Ash Brereton.

To define the rest of the domain, in TOOLS/DOMAINcfg, namelist_cfg was edited to include the definition of hybrid sigma-over-z-partial-steps vertical coordinates (ln_sco=.TRUE.) :

```
!-----------------------------------------------------------------------
&namcfg        !   parameters of the configuration
!-----------------------------------------------------------------------
   !
   ln_e3_dep   = .true.    ! =T : e3=dk[depth] in discret sens.
   !                       !      ===>>> will become the only possibility in v4.0
   !                       ! =F : e3 analytical derivative of depth function
   !                       !      only there for backward compatibility test with v3.6
   !                       !
   cp_cfg      =  "orca"   !  name of the configuration
   jp_cfg      =       12  !  resolution of the configuration
```

```
  jpidta      =    544   !  1st lateral dimension ( >= jpi )
  jpjdta      =    342   !  2nd    "         "    ( >= jpj )
  jpkdta      =     75   !  number of levels      ( >= jpk )
  jpiglo      =    544   !  1st dimension of global domain --> i =jpidta
  jpjglo      =    342   !  2nd    -                  -    --> j  =jpjdta
  jpizoom     =      1   !  left bottom (i,j) indices of the zoom
  jpjzoom     =      1   !  in data domain indices
  jperio      =      0   !  lateral cond. type (between 0 and 6)
/
!-----------------------------------------------------------------------
&namzgr        !   vertical coordinate
!-----------------------------------------------------------------------
  ln_zco      = .false.   !  z-coordinate - full    steps   (T/F)      ("key_zco" may also be defined)
  ln_zps      = .false.    !  z-coordinate - partial steps
  ln_sco      = .true.   !  s- or hybrid z-s-coordinate    (T/F)
  ln_isfcav   = .false.    !  ice shelf cavity
/
!-----------------------------------------------------------------------
&namzgr_sco    !   s-coordinate or hybrid z-s-coordinate               (default F)
!-----------------------------------------------------------------------
  ln_s_sh94   = .true.    !  Song & Haidvogel 1994 hybrid S-sigma   (T)|
  ln_s_sf12   = .false.   !  Siddorn & Furner 2012 hybrid S-z-sigma (T)| if both are false the NEMO
tanh stretching is applied
  rn_sbot_min =   10.0     !  minimum depth of s-bottom surface (>0) (m)
  rn_sbot_max = 6000.0     !  maximum depth of s-bottom surface (= ocean depth) (>0) (m)
  rn_hc       =  39.0      !  critical depth for transition to stretched coordinates
                        !!!!!!!  Envelop bathymetry
  rn_rmax     =    0.05    !  maximum cut-off r-value allowed (0<r_max<1)
                        !!!!!!!  hybrid z-s parameters
  nn_sig_lev = 39
  ln_s_melange = .true.
/
```

Before building the domain_cfg.nc file, it was necessary to copy over the code to enable these particular hybrid coordinates designed by James Harle:

```
cp $WORK/jdha/2017/nemo/trunk/NEMOGCM/TOOLS/DOMAINcfg/src/domzgr.f90.jelt
$TDIR/DOMAINcfg/src/domzgr.f90
```

A2. Extract bathymetry dataset and interpolate to model grid

Used the interpolated GEBCO 2014, 30 arc-second bathymetry created by Ash Brereton for the previous Caribbean model setup.

A3. Generate surface boundary forcing

Followed Nico Bruneau's recipe (https://github.com/NOC-MSM/NEMO_cfgs/wiki/ERA5-Forcing) to:

Loop over time to produce yearly forcing files - individual netCDF files for each field, for each year.
Handle netCDF scale and offset.
Use ncks to extract the region of interest.
Force longitudes to be positive.
Handle missing data.
Scale some variables to match the units convention in NEMO.
Copy the 'cumulated' variables (which come from a forecast) to the first timestep, as they are time-shifted.
Calculate specific humidity.
Generate a namelist for namsbc_core.

LL1: Existing recipe worked for NEMO v3.6 but not for this version, NEMO 4 (pre-release).

The main difference that seems to apply to NEMO (pre-release), is that namsbc_core is called namsbc_blk, and that there are some extra parameters set (which may also be specific to this particular config or already defined in namelist_ref) - in blue below.

```
!-----------------------------------------------------------------------
&namsbc_blk   !   namsbc_blk  generic Bulk formula                    (ln_blk = T)
!-----------------------------------------------------------------------
!             !  file name               ! frequency (hours) ! variable  ! time interp. !  clim  !
'yearly'/ ! weights                        ! rotation ! land/sea mask !
```

```
!          !                    !  (if <0  months)  !   name    !   (logical)  !  (T/F) ! 'monthly' !
filename                         ! pairing  ! filename      !
  sn_humi=       'ERA5_SPH',                  1,          'SPH',      .true.,    .false.,   'yearly',
 'caribbean_ERA5_msl_weights_bicubic_atmos.nc',    '',      'ERA5_LSM'
  sn_prec=       'ERA5_TP',                   1,          'TP',       .true.,    .false.,   'yearly',
 'caribbean_ERA5_msl_weights_bicubic_atmos.nc',    '',      'ERA5_LSM'
  sn_qlw =       'ERA5_STRD',                 1,          'STRD',     .true.,    .false.,   'yearly',
  'caribbean_ERA5_msl_weights_bicubic_atmos.nc',   '',      'ERA5_LSM'
  sn_qsr=        'ERA5_SSRD',                 1,          'SSRD',     .true.,    .false.,   'yearly',
 'caribbean_ERA5_msl_weights_bicubic_atmos.nc',    '',      'ERA5_LSM'
  sn_snow=       'ERA5_SF',                   1,          'SF',       .true.,    .false.,   'yearly',
 'caribbean_ERA5_msl_weights_bicubic_atmos.nc',    '',      'ERA5_LSM'
  sn_tair=       'ERA5_T2M',                  1,          'T2M',      .true.,    .false.,   'yearly',
 'caribbean_ERA5_msl_weights_bicubic_atmos.nc',    '',      'ERA5_LSM'
  sn_wndi=       'ERA5_U10',                  1,          'U10',      .true.,    .false.,   'yearly',
 'caribbean_ERA5_msl_weights_bicubic_atmos.nc',    '',      'ERA5_LSM'
  sn_wndj=       'ERA5_V10',                  1,          'V10',      .true.,    .false.,   'yearly',
 'caribbean_ERA5_msl_weights_bicubic_atmos.nc',    '',      'ERA5_LSM'
  sn_slp=        'SPH_ERA5_SP',               1,          'SP',       .true.,    .false.,   'yearly',
 'caribbean_ERA5_msl_weights_bicubic_atmos.nc',    '',      'ERA5_LSM'
  sn_tdif=       'SPH_ERA5_D2M',              1,          'D2M',      .true.,    .false.,
'yearly',   'caribbean_ERA5_msl_weights_bicubic_atmos.nc',    '',      'ERA5_LSM'
  !               !  bulk algorithm :
  ln_NCAR     = .true.    ! "NCAR"      algorithm   (Large and Yeager 2008)
  ln_COARE_3p0= .false.   ! "COARE 3.0" algorithm   (Fairall et al. 2003)
  ln_COARE_3p5= .false.   ! "COARE 3.5" algorithm   (Edson et al. 2013)
  ln_ECMWF    = .false.   ! "ECMWF"     algorithm   (IFS cycle 31)
  !
  cn_dir      = './fluxes/'      !  root directory for the location of the bulk files
  ln_taudif   = .false.   !  HF tau contribution: use "mean of stress module - module of the
mean stress" data
  rn_zqt      = 2.        !  Air temperature and humidity reference height (m)
  rn_zu       = 10.       !  Wind vector reference height (m)
  rn_pfac     = 1.        !  multiplicative factor for precipitation (total & snow)
```

```
  rn_efac     = 1.       !  multiplicative factor for evaporation (0. or 1.)
  rn_vfac     = 1.       !  multiplicative factor for ocean/ice velocity
                         !  in the calculation of the wind stress (0.=absolute winds or 1.=relative winds)
  ln_Cd_L12   = .false.  !  Modify the drag ice-atm and oce-atm depending on ice concentration
                         !  This parameterization is from Lupkes et al. (JGR 2012)
/
```

A4. Generate lateral boundary forcing from the global ORCA0083-N06 model run

The usual method is to use PyNEMO.

From https://pynemo.readthedocs.io/en/latest/intro.html :
"PyNEMO is a tool to set up the lateral boundary conditions for a regional [NEMO](http://www.nemo-ocean.eu/) model configuration. The tool is written in Python, largely within the [Anaconda](https://store.continuum.io/cshop/anaconda/) environment to aid wider distribution and to facilitate development. In their current form these tools are by no means generic and polished, but it is hoped will form a foundation from which something more formal can be developed. The following sections provide a quick-start guide with worked examples to help the user get up and running with the tool.

The tool essentially uses geographical and depth information from the source data (e.g. a global ocean simulation) and destination simulation (i.e. the proposed regional NEMO model configuration) to determine which source points are required for data extraction. This is done using a kdtree approximate nearest neighbour algorithm. The idea behind this targetted method is that it provides a generic method of interpolation for any flavour of ocean model in order to set up a regional NEMO model configuration. At present (alpha release) the tools do not contain many options, but those that exist are accessed either through a NEMO style namelist or a convient GUI."

Some relevant notes:
Section 8 onwards of [EA31FES_archer_Livljobs4](https://github.com/NOC-MSM/NEMO_cfgs/blob/master/recipes/docs/source/EA31FES_archer_Livljobs4.rst) and bottom of section 5 onwards of [SEAsia_archer_livljobs4](https://github.com/NOC-MSM/NEMO_cfgs/blob/master/recipes/docs/source/SEAsia_archer_livljobs4.rst).

For the Caribbean model, we want to generate boundary conditions in T, S, u, v, SSH from the global ORCA0083-N06 run, which has z-partial-steps as its vertical coordinate.

1. login to an ARCHER compute node with lots of memory
2. setup usual environment variables related to the regional model directory structure, e.g. $WORK, $INPUTS
3. install pynemo
4. create the appropriate inputs for pynemo (namelist and ncml (netCDF markup language) files)
5. (maybe transfer the data from JASMIN to a local directory - if the THREDDS server stuff doesn't work)
6. run pynemo to generate boundary conditions

However, PyNEMO did not work on ARCHER. It timed out with a memory error after a few hours, even on a compute node with 1 TB of RAM.

LL2: PyNEMO did not work on ARCHER, but ran for a few hours and then crashed with memory error. Others were successful in getting PyNEMO to work on different computers.

James Harle provided the lateral boundary conditions by using an alternative method (Matlab scripts).

A5. Generate lateral boundary forcing of tides

The existing tidal harmonics from the previous version of the Caribbean dev_surge model (Ash Brereton) were used, as the domain is identical. These are from TPXO7. Otherwise, the standard practice would be to use PyNEMO.

A6. Generate temperature and salinity initial conditions from the global model

Refer to the notes [generate_initial_conditions](https://github.com/NOC-MSM/NEMO_cfgs/blob/master/recipes/docs/source/generate_initial_conditions.rst) for comments and background.

Outline:

* Cut out a patch of T and S from a dataset larger than the regional domain.

* Use SCRIP tools to remap onto configurations horizontal coords

* Use SOSIE to remove land by extrapolating water laterally (relevant for zps to hybrid s-z interpolation later)

* Interpolate on-the-fly in NEMO to convert z-level to hybrid s-z coords.

Rough cut some initial conditions from parent (global) dataset
----
Make cut down from parent file : ORCA0083-N06.

First, obtain the data from JASMIN:

Copy T, S from the global run (ORCA0083-N006 in this case)

Login to JASMIN (make sure you have an account first)
(from *ljobs:)

```
exec ssh-agent $SHELL
ssh-add ~/.ssh/id_rsa_jasmin
ssh -A -X  cwilso01@jasmin-login1.ceda.ac.uk
ssh -X jasmin-xfer1
```

and copy the data from JASMIN to ARCHER:

```
scp -p /group_workspaces/jasmin2/nemo/vol1_OLD/ORCA0083-N006/means/2009/ORCA0083-N06_20090105d05T.nc cwi@login.archer.ac.uk:/work/n01/n01/cwi/caribbean/INPUTS/.

scp -p /group_workspaces/jasmin2/nemo/vol1_OLD/ORCA0083-N006/domain/bathy*nc cwi@login.archer.ac.uk:/work/n01/n01/cwi/caribbean/INPUTS/.
```

Cut down based on coordinates from [build_and_create_coordinates](https://github.com/NOC-MSM/NEMO_cfgs/blob/master/recipes/docs/source/build_and_create_coordinates.rst) namelist (`$START_FILES/namelist.input`). (Add a bit of a buffer):

```
module unload cray-netcdf-hdf5parallel cray-hdf5-parallel
module load cray-netcdf cray-hdf5
module load nco/4.5.0
cd $INPUTS

ncks -d x,2240,2790 -d y,1550,1898 $INPUTS/ORCA0083-N06_20090105d05T.nc $INPUTS/cut_down_Caribbean_20090105d05T.nc
```

Restore the parallel modules

```
module unload nco cray-netcdf cray-hdf5
module load cray-netcdf-hdf5parallel cray-hdf5-parallel
```

Use SCRIP tools to remap to the new grid

Now do interpolation onto child lateral grid.

Edit the namelists : `$INPUTS/namelist_reshape_bilin_initcd_votemper` and `$INPUTS/namelist_reshape_bilin_initcd_vosaline`. Here are the important bits of the first one (the second can be guessed from this).

```
&grid_inputs
   input_file = 'cut_down_Caribbean_20090105d05T.nc'
   nemo_file = 'coordinates.nc'
   datagrid_file = 'remap_data_grid_R12.nc'
   nemogrid_file = 'remap_nemo_grid_R12.nc'
   method = 'regular'
   input_lon = 'nav_lon'
   input_lat = 'nav_lat'
   nemo_lon = 'glamt'
   nemo_lat = 'gphit'
```

```
nemo_mask = 'none'
nemo_mask_value =  0
input_mask = 'none'
input_mask_value = 0
    /

    &remap_inputs
       num_maps = 1
       grid1_file = 'remap_data_grid_R12.nc'
       grid2_file = 'remap_nemo_grid_R12.nc'
       interp_file1 = 'data_nemo_bilin_R12.nc'
       interp_file2 = 'nemo_data_bilin_R12.nc'
       map1_name = 'R12 to nemo bilin Mapping'
       map2_name = 'nemo to R12 bilin Mapping'
       map_method = 'bilinear'
       normalize_opt = 'frac'
       output_opt = 'scrip'
       restrict_type = 'latitude'
       num_srch_bins = 90
       luse_grid1_area = .false.
       luse_grid2_area = .false.
    /
    &interp_inputs
       input_file = "cut_down_Caribbean_20090105d05T.nc"
       interp_file = "data_nemo_bilin_R12.nc"
       input_name = "potemp"
       input_start = 1,1,1,1
       input_stride = 1,1,1,1
       input_stop = 0,0,0,0
       input_vars = "deptht","time_counter"
    !   input_start = 1,1,1
    !   input_stride = 1,1,1
    !   input_stop = 0,0,75
    !   input_vars = "gdept"
       !!input_vars = "time_counter", "deptht", "y", "x"
       !input_name = "votemper"
       !input_start = 1,1,1,1
```

```
    !input_stride = 1,1,1,1
    !input_stop = 0,0,75,1
    !input_vars = "gdept","time_counter"

/

&interp_outputs
    output_file = "initcd_votemper.nc"
    output_mode = "create"
    output_dims = 'x', 'y', 'z', 'time_counter'
    output_scaling = "votemper|1.0"
    output_name = 'votemper'
    output_lon = 'x'
    output_lat = 'y'
    output_vars = "gdept", "time_counter"

/
&shape_inputs
    interp_file = 'data_nemo_bilin_R12.nc'
    output_file = 'weights_bilinear_R12.nc'
    ew_wrap     = -1
/
```

There are three steps for each of T and S.

scripgrid -> scrip -> scripinterp

You can build your own SCRIP in the TOOLS/WEIGHTS directory, or you can use an existing set of executables, e.g. in Valerie's directory

/work/n01/n01/valegu/EA31FES/trunk_NEMOGCM_r8395/TOOLS/WEIGHTS

```
scripgrid.exe namelist_reshape_bilin_initcd_votemper
scrip.exe namelist_reshape_bilin_initcd_votemper
scripinterp.exe namelist_reshape_bilin_initcd_votemper

scripgrid.exe namelist_reshape_bilin_initcd_vosaline
scrip.exe namelist_reshape_bilin_initcd_vosaline
scripinterp.exe namelist_reshape_bilin_initcd_vosaline
```

Use SOSIE tools to flood fill the parent initial conditions

```
module unload cray-netcdf-hdf5parallel cray-hdf5-parallel
module load cray-netcdf cray-hdf5
module load nco/4.5.0

ncks -d time_counter,0,0,1 -v vosaline initcd_vosaline.nc sosie_initcd_mask.nc
ncap2 -O -s 'where(vosaline<=30.) vosaline=0' sosie_initcd_mask.nc sosie_initcd_mask.nc
ncap2 -O -s 'where(vosaline>0.) vosaline=1' sosie_initcd_mask.nc sosie_initcd_mask.nc
ncrename -v vosaline,mask sosie_initcd_mask.nc
```

N.B. Check carefully that the mask variable in `sosie_initcd_mask.nc` only consists of 0 and 1.

Restore modules:

```
module unload nco/4.5.0
module unload cray-netcdf cray-hdf5
module load cray-netcdf-hdf5parallel cray-hdf5-parallel
```

Note that the notes [generate_initial_conditions](https://github.com/NOC-MSM/NEMO_cfgs/blob/master/recipes/docs/source/generate_initial_conditions.rst) suggest building the SOSIE tool. The rest of the instructions then apply to SOSIE v3beta and do not work for the latest version of the build, SOSIE v3, as the namelists are formatted differently.

Therefore, I used Jeff's previous build of SOSIE v3beta.

First, edit the namelists. Important bits below:

```
initcd_votemper.namelist

&ninput
ivect     = 0
lregin    = F
cf_in     = './initcd_votemper.nc'
cv_in     = 'votemper'
cv_t_in   = 'time_counter'
jt1       = 0
```

```
jt2       = 0
jplev     = 0
cf_x_in   = './initcd_votemper.nc'
cv_lon_in = 'x'
cv_lat_in = 'y'
cf_lsm_in = './sosie_initcd_mask.nc'
cv_lsm_in = 'mask'
ldrown    = T
ewper     = -1
vmax      =  1.E6
vmin      = -1.E6
ismooth   = 0
/

&n3d
cf_z_in  = 'initcd_votemper.nc'
cv_z_in  = 'gdept'
cf_z_out = 'initcd_votemper.nc'
cv_z_out = 'gdept'
cv_z_out_name = 'gdept'
ctype_z_in = 'z'
ctype_z_out = 'z'
/

&nhtarget
lregout    = F
cf_x_out   = 'initcd_votemper.nc'
cv_lon_out = 'x'
cv_lat_out = 'y'
cf_lsm_out = ''
cv_lsm_out = ''
lmout      = F
!rmaskvalue = -9999
lct        = F
t0         = 0.
t_stp      = 0.
ewper_out  = -1
```

```
/

&noutput
cmethod  = 'bilin'
cv_t_out = 'time_counter'
cv_out   = 'votemper'
cu_out   = 'C'
cln_out  = 'Temperature'
cd_out   = '.'
!!
csource  = 'ORCA0083-N06'
ctarget  = 'Caribbean'
cextra   = '2009'
/
```

And for salinity:

```
initcd_vosaline.namelist

&ninput
ivect     = 0
lregin    = F
cf_in     = './initcd_vosaline.nc'
cv_in     = 'vosaline'
cv_t_in   = 'time_counter'
jt1       = 0
jt2       = 0
jplev     = 0
cf_x_in   = './initcd_vosaline.nc'
cv_lon_in = 'x'
cv_lat_in = 'y'
cf_lsm_in = './sosie_initcd_mask.nc'
cv_lsm_in = 'mask'
ldrown    = T
ewper     = -1
vmax      =  1.E6
vmin      = -1.E6
```

```
ismooth   = 0
/

&n3d
cf_z_in  = 'initcd_vosaline.nc'
cv_z_in  = 'gdept'
cf_z_out = 'initcd_vosaline.nc'
cv_z_out = 'gdept'
cv_z_out_name = 'gdept'
ctype_z_in = 'z'
ctype_z_out = 'z'
/

&nhtarget
lregout    = F
cf_x_out   = 'initcd_vosaline.nc'
cv_lon_out = 'x'
cv_lat_out = 'y'
cf_lsm_out = ''
cv_lsm_out = ''
lmout      = F
!rmaskvalue = -9999
lct        = F
t0         = 0.
t_stp      = 0.
ewper_out  = -1
/

&noutput
cmethod  = 'bilin'
cv_t_out = 'time_counter'
cv_out   = 'vosaline'
cu_out   = 'psu'
cln_out  = 'Salinity'
cd_out   = '.'
!!
csource  = 'ORCA0083-N06'
```

```
ctarget  = 'Caribbean'
cextra   = '2009'
/
```

Then run SOSIE v3beta from Jeff's executable:

```
/home/n01/n01/jelt/sosie/bin/sosie.x -f initcd_votemper.namelist
/home/n01/n01/jelt/sosie/bin/sosie.x -f initcd_vosaline.namelist
```

Check the files look okay.

Then, follow the instructions for interpolating in z on-the-fly.
In my case, the code in MY_SRC already had the relevant subroutines, so I did not need to rebuild NEMO.

Also, as I had made a mask for SOSIE earlier, I simply copied it: `cp sosie_initcd_mask.nc initcd_mask.nc`.

There is a typo in the instructions:

```
ncap2 -O -s 'gdept_4D[time_counter,z,y,x]=gdept_4D' tmp.nc initcd_depth.nc
rm tmp.nc
```

should read

```
ncap2 -O -s 'gdept_4D[time_counter,z,y,x]=gdept_3D' tmp.nc initcd_depth.nc
rm tmp.nc
```

Other than that, they can be followed 'as is'.

Note that it may be necessary to reduce the timestep dramatically for initialisation, due to fast adjustment.

LL4: It would help a new user if there was a basic description of the tools referred to in the recipes, e.g. SOSIE and SCRIP.

LL5: Existing recipes that refer to external/internal code/data, which is potentially evolving, may become invalid and there is sometimes insufficient time to fix the recipes, either specifically or generally, within a project.

A7. Activate the full surface flux bulk parameterisation for the mixed layer

In namelist_cfg,

```
!-----------------------------------------------------------------------
&namsbc_blk   !   namsbc_blk  generic Bulk formula                    (ln_blk = T)
!-----------------------------------------------------------------------
...
  !                    !  bulk algorithm :
   ln_NCAR      = .true.   ! "NCAR"      algorithm   (Large and Yeager 2008)
/
```

A8. Activate the thermodynamic equation of state

In namelist_cfg,

```
!-----------------------------------------------------------------------
&nameos        !   ocean physical parameters
!-----------------------------------------------------------------------
   ln_teos10    = .true.         !  = Use TEOS-10 equation of state
/
```

A9. Activate the tidal ramping

This helps the model remain stable when it is initialised from the temperature and salinity initial conditions of the global model. The tidal forcing is scaled by a parameter which varies linearly from 0 to 1 over a time period set by the parameter 'rdttideramp' in namelist_cfg.

```
!-----------------------------------------------------------------------
&nam_tide      !   tide parameters
!-----------------------------------------------------------------------
...
  ln_tide_ramp= .true.   ! linearly increase tidal forcing at beginning - only for spinup
   rdttideramp =    30.
/
```

A11. Tune tracer diffusivity and adjust model timestep

A timestep of 240 s was found to be optimal, although for the first 30 days of spinup a smaller (40 s) timestep was used to keep the solution stable for initial adjustment.

A12. Activate the diagnostics, including on-the-fly tidal harmonic analysis

For the on-the-fly tidal harmonic analysis, (re-)build NEMO with the 'key_harm_ana' compilation flag in CONFIG/cpp_caribbean.fcm , the contents of which should read:

bld::tool::fppkeys key_nosignedzero key_diainstant key_mpp_mpi key_iomput key_zdfgls key_harm_ana

... for the case of the GLS vertical diffusion scheme (key_zdfgls).

The following files should also be placed into MY_SRC for tidal analysis, before compilation: diaharmana.F90, step_oce.F90, step.F90, bdytides.F90 . These are MY_SRC in the Caribbean Github repository.

In the EXP00 run directory, file-def-nemo-opa.xml needs to be edited to control which diagnostics are to be calculated and output.

LL6 : The instructions for choosing which tidal analysis routine to use were somewhat unclear. There are alternative tidal analysis routines available, with more harmonics included. This is an active area of development at NOC.

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