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Convection and waves on small planets and the real Earth

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Convection and waves on small planets and the real Earth

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The ECMWF plans foresee a horizontal resolution upgrade to T2047 (10 km) in 2015, and moving toward T3999 (5 km) around 2020. Exploratory forecasts at T7999 resolution (equivalent to about 2.5 km horizontal gridlength) have recently been presented by *Wedi et al*. (2012). The particular challenge at such high resolutions is that deep convective motions become gradually more resolved. Consequently the optimal partitioning in the model between resolved and sub-grid vertical motions and condensation processes has to be reconsidered. Also one wants to estimate the horizontal resolution beyond which the global forecasting system could eventually be run without a deep convection parametrization whilst improving the forecast skill on the medium to monthly time scales for both middle-latitude and tropical regions.

At the high resolutions being envisaged, not only the simulations but also the data storage and processing are extremely costly, rendering extensive experimentation and developments impractical on current computer systems. In order to overcome these limitations, *Wedi & Smolarkiewicz* (2009) set up a prototype reduced planet version of the atmospheric model used in the Integrated Forecasting System (IFS) without model physics. This enabled the development and efficient evaluation of the non-hydrostatic dynamical core of the model. The small-scale prototype approach is extensively used in the engineering community where, for example, the aerodynamic properties of a small-scale object are experimentally determined in a wind tunnel, and the performance data can then be up-scaled to the true sized object via a numerical model that is written in non-dimensional form.

Our goal is to develop a scaled version of the IFS with full physics that not only allows the model to be applied to planets of different size and gravity, but also faithfully reproduces the general circulation of the Earth. The final goal will be to have a system that permits deep convective motions while maintaining a realistic large-scale circulation. Such a system, which necessarily involves some approximations, has been pioneered by *Kuang et al*. (2005), *Pauluis et al*. (2006) and *Garner et al*. (2007), but has never been developed for a complex numerical weather prediction system.

In the following we present step by step, with increasing complexity, the various reduced planet configurations that have been used, and illustrate what each configuration can and cannot do.

Aqua planet and scaling laws

An ideal prototype is the Aqua planet. In this configuration, as proposed by *Hoskins & Neale* (2000), the whole planet is covered by water and the sea surface temperatures (SSTs) are specified. For an Earth-like simulation, typically a zonally symmetric SST distribution is chosen peaking at 27°C at the equator and decreasing to 0°C beyond 60° latitude. Furthermore, the Sun is fixed over the equator, thus there is no seasonal cycle. The advantage of the Aqua planet is that it removes complications due to land-surface/atmosphere interactions such as orographic drag, soil hydrology and the diurnal cycle over land. Also it avoids the complications of scaling the orography and height of the vegetation for planets of different size.

The reduced planet system has the following scalings.

- ***Horizontal length scale.*** The Earth's radius R_a is divided by a factor γ_R, and consequently the horizontal length scale L is also reduced by the same factor.
- ***Vertical length scale.*** The vertical length scale Z is conveniently reduced by a factor γ_g by increasing the gravity by the same factor, recognizing that the scale height H of the atmosphere is given by the ratio of a mean temperature *T* times the gas constant *R* and the gravity *g*.
- ***Time scale.*** The time scale *t* is reduced by a factor γ_Ω by increasing the rotation rate Ω of the planet by a factor γ_Ω which is equivalent to reducing the length of the day.

Consequently, choosing various values for the factors γ_R, γ_g and γ_Ω allows a choice of configurations. For example, the full Aqua planet has $\gamma_R = \gamma_\Omega = \gamma_g = 1$. More detailed information about the scaling is given in the Appendix.

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While applying these scalings, the atmospheric motions on the reduced planet can be faithfully reproduced with respect to the full planet only if the two non-dimensional numbers, namely the Rossby and Richardson numbers, are kept constant. The Rossby number measures the ratio between the acceleration and the Coriolis force or rotational acceleration, while the Richardson number measures the relative importance of the buoyancy acceleration to the acceleration due to vertical advection (i.e. the importance of convection through the Brunt Väisälä frequency). Finally the Rossby and Richardson numbers can be cast into one single parameter, the Lamb parameter, which can be interpreted as the ratio between the planet rotational speed and the internal gravity wave phase speed. Interestingly, the Lamb parameter does not involve the horizontal wind speed which is an internal parameter. This means that when conserving the Lamb parameter, the wind field on the reduced planet is the same as on the full planet.

Isolated thunderstorm on a reduced planet

The first example is the simulation of an isolated split thunderstorm that evolves into a supercell thunderstorm. This is achieved by initialising the model with a convectively unstable sounding with rotational wind shear that is the same everywhere.

The non-hydrostatic version of the IFS is run for two hours with full physics, but without deep convection parametrization at truncation T511. For this experiment, the Earth's radius is scaled by a factor $\gamma_R = 12.5$, giving an effective horizontal resolution of about 3 km, but the vertical length and time scales are not changed (i.e. $\gamma_g = \gamma_\Omega = 1$). This means that convective systems have the same size as on the real planet, while occupying a larger portion of the reduced planet.

Figure 1a shows the temperature and wind at the first model level along with the three-dimensional distribution of hydrometeors (i.e. cloud droplets, cloud ice, rain and snow). Also the accumulated surface precipitation and low-level wind is shown in Figure 1b. The results can be directly compared to corresponding simulations with limited area models because, given the small size of convective systems, the Coriolis effects due to the planet's rotation can be neglected. From these results it can be concluded that the reduced planet version of the IFS can be used to simulate intense isolated thunderstorms.

In this somewhat academic study we have indeed saved roughly a factor γ_R^2 (about 156) in computer time and data storage with respect to the actual 3 km full planet version of the model. However, by only scaling the planet radius, it is not possible to realistically represent the large-scale circulation or the interaction between the convective and synoptic-scale motion systems.

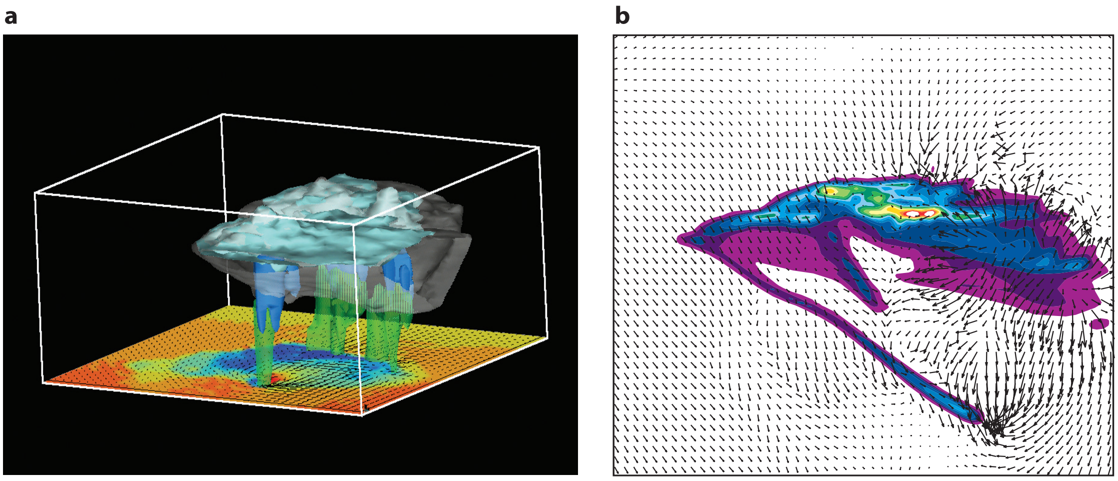

Figure 1 Non-hydrostatic simulation after 2 hours at resolution T511 with γ_R =12.5 (3 km resolution) and $\gamma_g = \gamma_\Omega = 1$ in an environment with rotational wind shear. (a) Temperature (colour shading) and wind at the first model level, as well as the 0.5 g kg^{-1} iso-surfaces of cloud droplets (blue), cloud ice (cyan), rain (green) and snow (white). (b) Accumulated surface precipitation and low-level winds; the contour interval is 0.5 mm. The vortex to the right (right mover) is characteristic of vortices that in nature favour the formation of tornadoes.

Dry baroclinic waves on the super-rotating planet

The synoptic scales on the reduced planet can only be faithfully reproduced with respect to the full planet if the Lamb parameter is conserved. This means that the rotation rate of the reduced planet has to be increased accordingly, so that both the characteristic wavenumber and frequency of the planetary Rossby waves remain unchanged.

To illustrate the scaling of dry synoptic waves, we employ a dry baroclinic test case following *Jablonowski & Williamson* (2006), where the model is initialised with a meridional temperature gradient and a geostrophically-balanced wind field with a strong zonal upper-level jet. The hydrostatic dynamical core of the model is then run without moist physics for ten planetary rotations at truncation T159, with the vertical length scale unchanged ($\gamma_g = 1$) and the other scaling factors as follows.

- $\gamma_R = \gamma_\Omega = 1$ which correspond to a 125 km horizontal resolution and rotation rate of 24 hours or 86,400 s (Figure 2a).
- $\gamma_R = \gamma_\Omega = 1{,}000$ which correspond to a 125 m horizontal resolution and rotation rate of 86.4 s (Figure 2b).

The results in Figure 2 show that the synoptic waves are quasi-identical in both simulations, indicating that the scaling is correct. However, nothing has been gained from the reduced planet simulations in terms of computer time and data storage; with respect to the full planet simulations the length of the integrations is still ten rotations, but the length of the day and the model time step have to be reduced accordingly. Furthermore, no model physics has been used in these planetary simulations. Had we done so, Figures 2a and 2b would no longer be identical. The reason being that, as the time scale of the synoptic forcing has been shortened, the physics also has to be accelerated. This is discussed next.

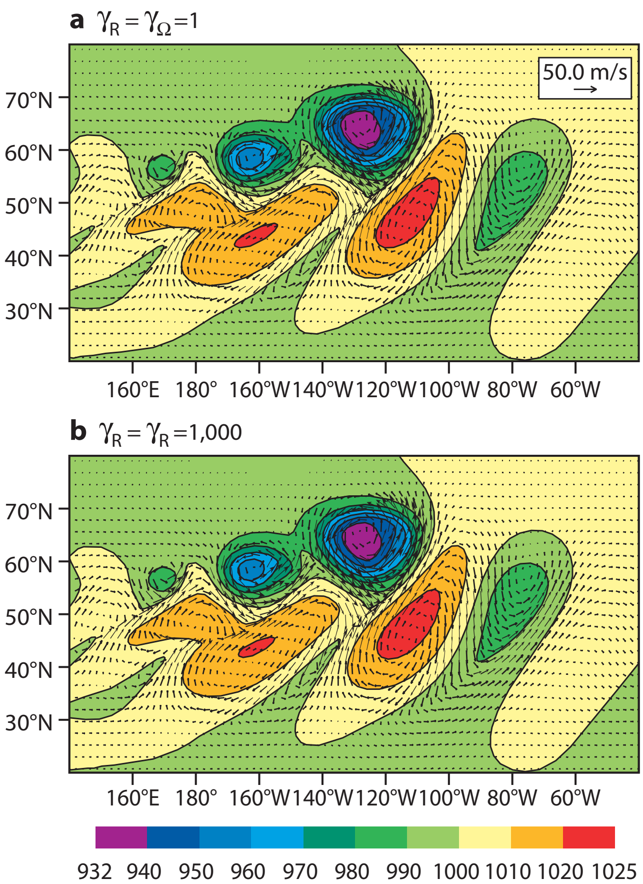

Figure 2 Baroclinic wave train with surface pressure contours (hPa) and wind field, in hydrostatic simulations at resolution T159 with $\gamma_g = 1$ and (a) $\gamma_R = \gamma_\Omega = 1$ (125 km resolution and 86,400 s rotation rate) and (b) $\gamma_R = \gamma_\Omega = 1{,}000$ (125 m resolution and 86.4 s rotation rate) after ten rotations of the planet. As the rotation rate of the planet has also been increased by a factor γ_Ω, (a) corresponds to a real time of 864,000 s and (b) to a real time of 864 s.

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The global circulation and the shallow atmosphere

The most effective way to accelerate the physics consistently with the shortening of the synoptic flow time-scale is by scaling the gravity. This leads to a system where the horizontal length, vertical length and time scales are all reduced by the same factor (i.e. $\gamma_R = \gamma_\Omega = \gamma_g = \gamma$) – this is referred to as SASE (Shallow Atmosphere Small Earth).

In this system with reduced scaled height, the diabatic forcing is naturally increased through radiative and surface heating as is the response through stratiform heating and convective heating and transport. Note that this system gives results that are identical to those in Figure 2 for the dry baroclinic wave case. However, a few precautions have to be taken in the physics concerning the internal constants that have been given absolute values instead of generally scaled values. In the model this affects the microphysical time-scales which have to be scaled by γ_Ω, as well as the turbulent length scale, and the entrainment and detrainment rates in the convection parametrization. The latter had to be rescaled by γ_g as the scale height of the atmosphere has been reduced.

The general circulation on the Aqua planet and its climate is simulated by starting from a balanced state, using a six-months spin-up forecast. A four-member ensemble is then generated by integrating the model for one year at spectral truncation T159. Figure 3a shows the annual mean precipitation (mm day^{-1}) on the real Earth as obtained from the GPCP2.2 dataset. The other panels in Figure 3 show the results for the full and reduced Aqua planet using the deep convection parametrization but different scalings.

- The full Aqua planet with $\gamma_R = \gamma_\Omega = \gamma_g = 1$ (Figure 3b) exhibits a distinctive tropical band with a precipitation rate of about 11 mm day^{-1}, and equatorially symmetric middle-latitude storm tracks. Its climate is in qualitative agreement with what is observed for the real Earth (Figure 3a).
- The reduced Aqua planet with $\gamma_R = \gamma_\Omega = 8$ and $\gamma_g = 1$ (Figure 3c), which has the same scaling as used for Figure 2b, produces a split inter-tropical convergence zone and middle-latitude storm tracks that are shifted too far poleward. It is therefore not an accurate scaled version of the full Aqua planet.
- Using the SASE system with $\gamma_R = \gamma_\Omega = \gamma_g = 8$ (Figure 3d), an accurate small-scale version of the climate on the full planet is obtained.

The convectively-coupled waves in the tropical band are analysed in Figure 4 using wavenumber frequency diagrams of the outgoing longwave radiation. Satellite observations (Figure 4a) reveal the dominant tropical wave types which are the eastward propagating Kelvin waves and the westward propagating equatorial Rossby wave. The Madden-Julian oscillation is also apparent as a distinct mode. It can be seen that the dominant wave types are reasonably reproduced for the full Aqua planet simulations (Figure 4b), but the amplitudes are larger than those observed because these waves can freely circumnavigate the equator without being disturbed by land effects. However, the tropical wave spectra, and in particular the Kelvin waves, are heavily distorted for the reduced Aqua planet with $\gamma_R = \gamma_\Omega = 8$ and $\gamma_g = 1$ (Figure 4c), but faithfully reproduced with the SASE system using $\gamma_R = \gamma_\Omega = \gamma_g = 8$ (Figure 4d).

The SASE system is shown to provide the correct scaling of the full planet and therefore allows the model to be applied to planets of different size and gravity. Unfortunately, nothing has been gained in terms of computer time, and we have still not achieved our final goal of resolving deep convection. Indeed, in the SASE system the scale of the convection has also been reduced. This follows from observational evidence showing that the horizontal scale of convective clouds is related to the scale height. Also, from a scale analysis it follows that for SASE the time scale of convection has been reduced, but the vertical velocity is the same as for the full Aqua planet simulation.

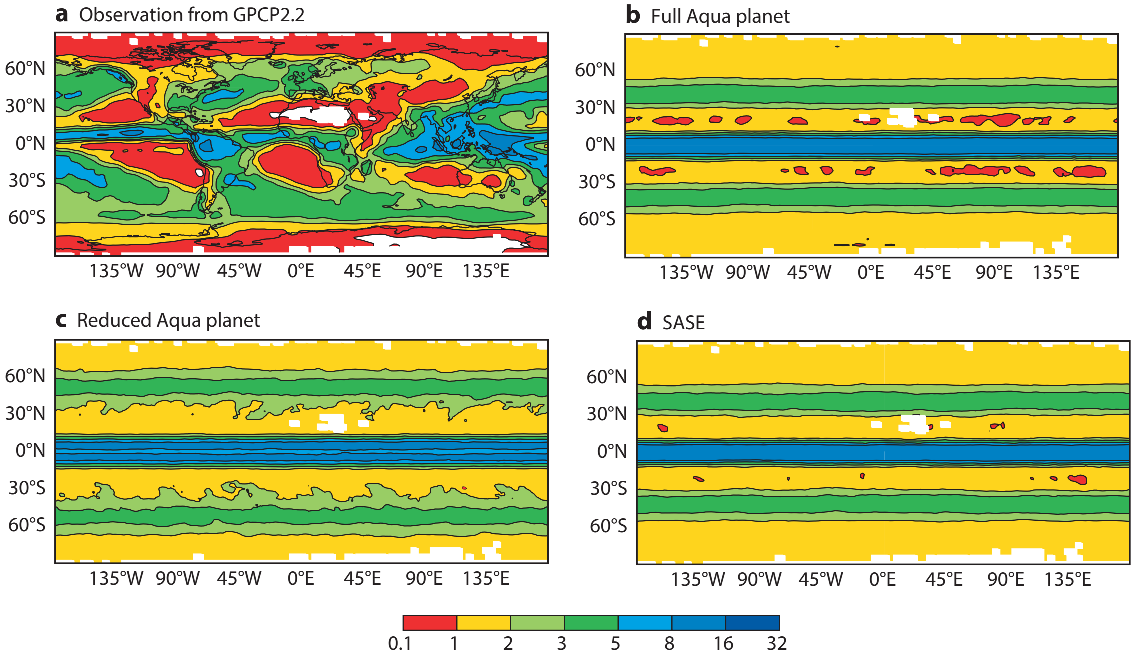

Figure 3 Annual mean daily global precipitation (mm). (a) Observations from the GPCP2.2 precipitation climatology dataset. Also shown are a one-year integration at T159 of a four-member ensemble with deep convection parametrization using (b) the full Aqua planet with $\gamma_R = \gamma_\Omega = \gamma_g = 1$, (c) the reduced Aqua planet with $\gamma_R = \gamma_\Omega = 8$ and $\gamma_g = 1$, and (d) the SASE system with $\gamma_R = \gamma_\Omega = \gamma_g = 8$.

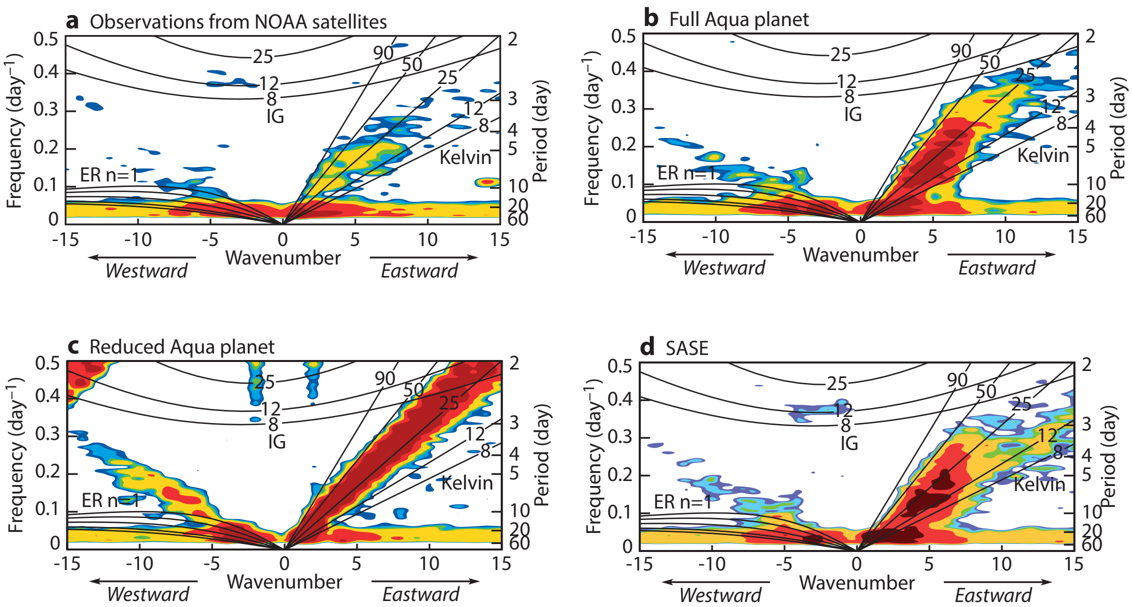

Figure 4 Same as Figure 3, but for the wavenumber frequency spectra of the outgoing longwave radiation with observations from the NOAA satellites. The data has been averaged between 10°S and 10°N, a background spectrum has been substracted, and only the symmetric part of the spectrum is displayed. Spectra include the theoretical dispersion relations with external gravity wave phase speed c = (gH)½ as a function of equivalent depth *H*. The characteristic tropical wave types include the eastward propagating Kelvin waves, the westward propagating Equatorial Rossby (ER) waves, and the Inertia Gravity (IG) waves. Note that Kelvin waves behave like gravity waves, and that the Madden-Julian Oscillation corresponds to the spectral peak in the wavenumber 1–2 and period 20–60 days band.

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Towards global resolved convection

Our final aim is to efficiently resolve deep convection on the reduced planet, while maintaining a realistic interaction between the convection and the large-scale circulation. The basic idea is to reduce the gap between the convective and large-scale motions. This can be achieved either by reducing the scale of the synoptic circulations, therefore bringing them closer to the convective scales, or by increasing the scale of the convective motions.

The former approach was proposed by *Kuang et al*. (2005) and called DARE (Diabatic Acceleration and Rescaling). In this system $\gamma_\Omega = \gamma_R = \gamma$ and $\gamma_g = 1$ with rescaling of the external forcings. In addition, we considered the alternative Deep Atmosphere Small Earth (DASE) approach, where DARE is combined with the scaling of the SASE system giving $\gamma_\Omega = \gamma_R = \gamma$ and $\gamma_g = \gamma^{-1}$. This means that the scale height of the atmosphere is increased with a consequent increase in the horizontal scale of convective motions – see Box A for more information.

Figure 5 displays the annual mean precipitation rate, similar to that shown in Figure 3, but for hydrostatic integrations without convection parametrization for:

- The full Aqua planet at truncation T159 and T1279 (Figures 5a and 5b).
- The reduced Aqua planet at T159 with γ=8 using the DARE and DASE configurations (Figures 5c and 5d).

The T159 integration without convection parametrization (Figure 5a) greatly overestimates the equatorial precipitation compared to the control run with deep convection parametrization (Figure 3b). But, when increasing the resolution to T1279 (Figure 5b), the results without convection parametrization become comparable to the control.

If the DARE or DASE configurations at T159 (with γ=8 using the same time step as the T1279 integration) are able to reproduce the T1279 results, then we have indeed a system that allows a saving in computer time of order γ^3 (i.e. order 512). However, DARE (Figure 5c) essentially only reproduces the results of the T159 integration (Figure 5a). This was expected as we are not yet in the non-hydrostatic regime. In contrast, the results with DASE (Figure 5d) become comparable to the T1279 full planet integration and also to the T159 integration preformed with deep convection parametrization (Figures 3b and 3d).

As well as considering the distribution of precipitation, it is worthwhile examining whether DASE can produce realistic tropical wave spectra. Figure 6 displays the tropical wave spectra for the simulations illustrated in Figure 5. In the T159 integration without convection parametrization, as well as in DARE, the wave spectra are broad and noisy (Figures 6a and 6c). However, at T1279 (Figure 6b) the wave spectra become comparable to the integration with deep convection (Figure 3b).The dominant wave types are also reasonably reproduced with DASE (Figure 6d).

The results given in Figures 5 and 6 show that the new fully scaled system DASE is indeed a step forward in resolving convection as it is able to mimic both the mean climate and the wave motions of the T1279 full planet integrations.

DARE and DASE scaling

A

DARE (Diabatic Acceleration and Rescaling) uses $\gamma_\Omega = \gamma_R = \gamma$ and $\gamma_g = 1$, and requires the rescaling (acceleration) of the external forcing including radiation and surface fluxes in order to increase the forcing of convective-scale motions. A key aspect of DARE is that the vertical scale remains unchanged. Thus, even though the convection is driven more strongly by a factor γ_Ω, the natural horizontal scale of the convection is unchanged, and hence is a factor γ_Ω closer to the synoptic scale. Yet, DARE requires non-hydrostatic simulations to take advantage of the reduced synoptic/convective scale separation. In fact, the quasi-nonhydrostatic parameter, which scales as the square of the aspect ratio (i.e. *H*/*L* where *H* is the scale height and *L* is the horizontal length scale), is not large enough to allow a transition into the resolved range.

The Deep Atmosphere Small Earth (DASE) approach combines DARE with the scaling of the SASE system, but increases H by reducing gravity, and consequently increases the horizontal scale of convective motions. In DASE, we therefore have $\gamma_\Omega = \gamma_R = \gamma$ and $\gamma_g = \gamma^{-1}$.

While DASE increases the convective scales, and increases the aspect ratio and vertical motions by a factor γ_Ω^2, it also reduces the synoptic scales. The convective and synoptic motions are therefore closer in scales, and can be resolved simultaneously over a time-step equivalent to the one used in a simulation γ times wider in the horizontal direction, γ times narrower in the vertical direction and γ times longer in time. The quasi-nonhydrostatic condition becomes sufficiently large to allow a transition into the resolved range.

The DARE and DASE systems include the physics scaling with the radiative flux, surface heat and momentum fluxes, microphysical time scales, and fall velocity of precipitation.

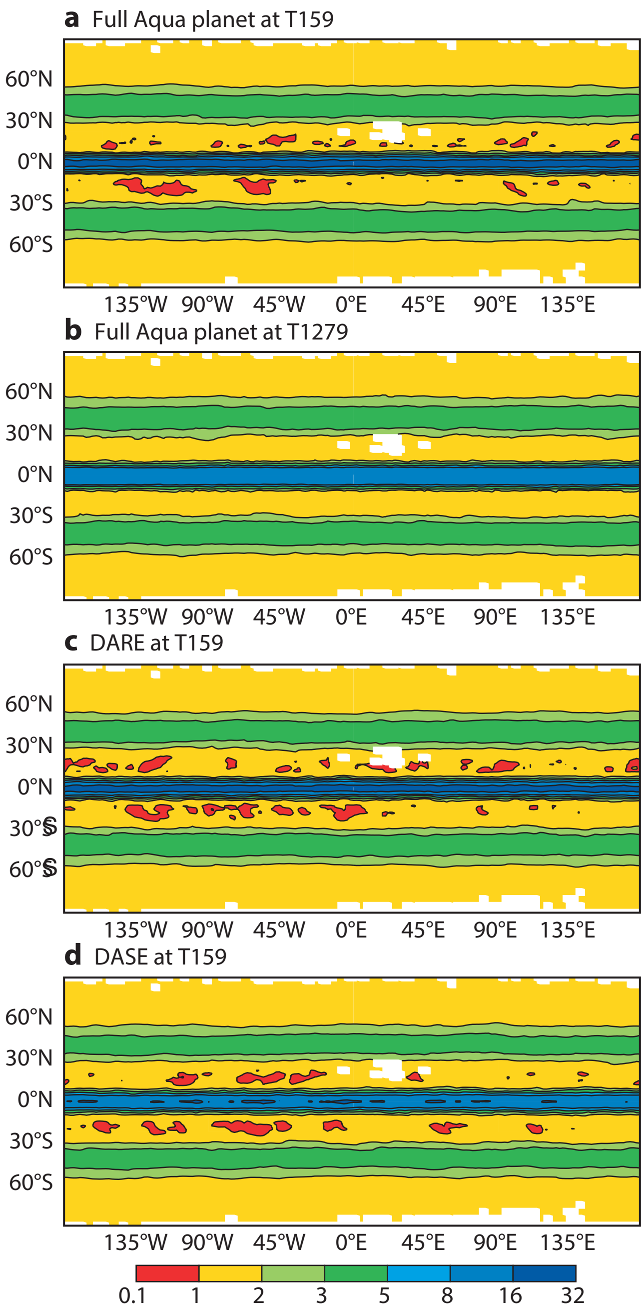

Figure 5 Annual mean daily global precipitation (mm) for hydrostatic integrations without deep convection parametrization for the full Aqua planet ($\gamma_R = \gamma_\Omega = \gamma_g = 1$) at (a) T159 and (b) T1279, and the reduced Aqua planet at T159 with (c) DARE ($\gamma_R = \gamma_\Omega = 8$ and γ_g=1) and (d) DASE ($\gamma_R = \gamma_\Omega = 8$ and $\gamma_g = 1/8$).

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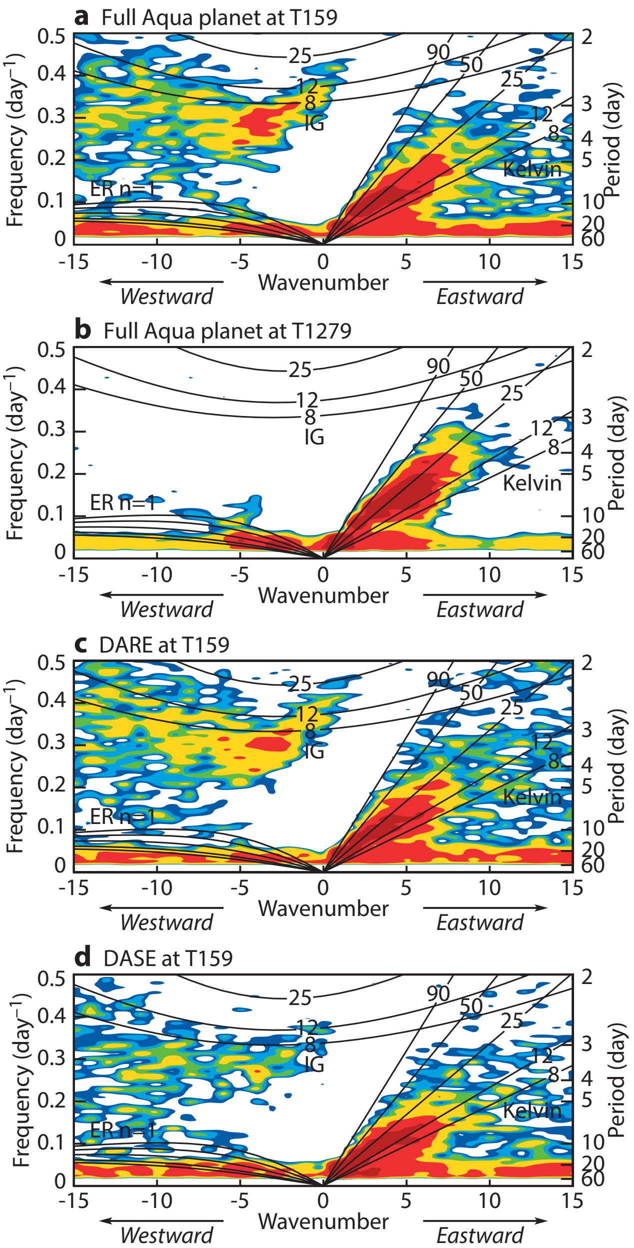

Figure 6 Same as Figure 4, but with wavenumber frequency spectra corresponding to the simulations in Figure 5.

Perspectives

A scaled version of the IFS has been developed; it can be applied to planets of different size and gravity. Also, a slightly different alternative system dubbed 'Deep Atmosphere Small Earth' opens the potential to efficiently mimic resolved deep convection. This constitutes ground-breaking research, and the prototype version will be available to users of OpenIFS from Cy39r1 onward. There are however evident limitations in the method in that it is not possible to rescale the microphysical processes in a way that is consistent both with the small- and large-scale processes. We estimate that values of γ up to 10 might still provide sufficient physical realism, while providing efficient high-resolution experimentation. In particular, we intend to study the transition from parametrized to resolved convection in the 10 km to 1 km resolution range, and the effects of convectively generated gravity waves on the circulation in the stratosphere and mesosphere.

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Appendix. Scaling parameters and non-dimensional numbers

External control: Scaling parameters

Scaling of the external planetary parameters, planetary radius R_a, gravity g, and rotation speed Ω by a factor γ leads to the scaling of horizontal length L, height scale Z and time scale t as follows.

$$R'_a = R_a / \gamma_R \quad \rightarrow \quad L' = L / \gamma_R$$

$$g' = g\gamma_g \quad \rightarrow \quad H' = \frac{RT}{\gamma_g g} \rightarrow H / \gamma_g \rightarrow Z' = Z / \gamma_g$$

$$\Omega' = \Omega\gamma_\Omega \quad \rightarrow \quad t' = t / \gamma_\Omega$$

Here T is the mean temperature and R the gas constant.

Non-dimensional characteristic numbers

Non-dimensional numbers can be derived that include the Rossby number, Ro, the Richardson number, Ri, and the Lamb parameter, La, involving also the Brunt Väisälä frequency N and the internal gravity wave phase speed c.

$$N^2 = \frac{g}{\theta}\frac{\Delta\theta}{H} \quad c = NH$$

$$Ro = \frac{U}{2\Omega R_a} \qquad Ri = \frac{N^2 H^2}{U^2} \rightarrow \quad La = Ro^{-2} Ri^{-1} = \frac{4\Omega^2 R_a^2}{c^2}$$

Further reading

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