IFS at high resolution

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Overview of presentation

Stabilisation of time-stepping

- pressure related instabilities at high resolution - analysis of stability

NH vs H dynamics at high resolution

- jetstream over Himalaya range
- trapped lee waves over UK

Pressure related instabilities

Hybrid vertical coordinate definition

$$\pi = A(\eta) + B(\eta)\pi_s \tag{1}$$

Monotonicity surface pressure

Monotonic surface pressure defined as π_s for which monotonicity of hybrid coordinate $\pi = A + B\pi_s$ is lost $\frac{\partial A}{\partial \eta} + \frac{\partial B}{\partial \eta}\pi_s \leq 0$.

Monotonicity surface pressure of operational coordinate

Currently 303hPa. On Mount Everest is 315hPa +- 8hPa. But what is happening with time stepping stability when we approach such values ?

Pressure related instabilities

IFS NH use iterative-centered implicit (ICI) scheme, that is iterative approximation of trapezoidal scheme

Trapezoidal scheme

$$\frac{X^{t+\Delta t} - X^t}{\Delta t} = \frac{\mathcal{M}(X^{t+\Delta t}) + \mathcal{M}(X^t)}{2} \qquad (2)$$

iterative approximation

ICI scheme - n-th iteration

$$\frac{X^{t+\Delta t(n)} - X^t}{\Delta t} = \frac{\mathcal{R}(X)^{t+\Delta t(n-1)} + \mathcal{R}(X)^t}{2} + \mathcal{L}^* \cdot \frac{X^{t+\Delta t(n)} + X^t}{2}. \qquad (3)$$

with nonlinear residual $\mathcal{R} = \mathcal{M} - \mathcal{L}^*$ and first guess $\mathcal{R}(X^{t+\Delta t(0)}) = \mathcal{R}(X^t)$. $\mathcal{L}^*$ is linear operator derived from $\mathcal{M}$ assuming small perturbations around reference state X^* - isothermal, flat, motionless, hydrostatically balanced.

Pressure related instabilities

To study stability - $\mathcal{M}$ is replaced by linear operator $\overline{\mathcal{M}}$ that describe small perturbations around reference state isothermal, flat, motionless, hydrostatically balanced $\overline{X}$.

ICI scheme - n-th iteration - linear

$$\frac{X^{t+\Delta t(n)} - X^t}{\Delta t} = \frac{\overline{\mathcal{R}}(X)^{t+\Delta t(n-1)} + \overline{\mathcal{R}}(X)^t}{2} + \mathcal{L}^* \cdot \frac{X^{t+\Delta t(n)} + X^t}{2}. \qquad (4)$$

with linear residual $\overline{\mathcal{R}} = \overline{\mathcal{M}} - \mathcal{L}^*$ and first guess $\overline{\mathcal{R}}(X^{t+\Delta t(0)}) = \overline{\mathcal{R}}(X^t)$. When $M_i = (\mathbf{I} - \tau\mathcal{L}^*)^{-1}\tau\overline{\mathcal{R}}$ and $M_c = (\mathbf{I} - \tau\mathcal{L}^*)^{-1}\left(\mathbf{I} + \tau\mathcal{L}^* + \tau\overline{\mathcal{R}}\right)$ we can write

Matrix form of ICI scheme

$$\hat{X}_d^{t+\Delta t(n)} = M_i \hat{X}_d^{t+\Delta t(n-1)} + M_c \hat{X}_d^t \qquad (5)$$

$$\hat{X}_d^{t+\Delta t(n)} = M_n \hat{X}_d^t = \left(M_i^n + \sum_{k=0}^{n-1} M_i^k . M_c \right) \hat{X}^t. \qquad (6)$$

Eigenvalues of M_i - rate of convergence, eigenvalues of M_n - stability

Pressure related instabilities

Stability of ICI time stepping with 1 iteration. Results obtained for wave number $k = 0$.

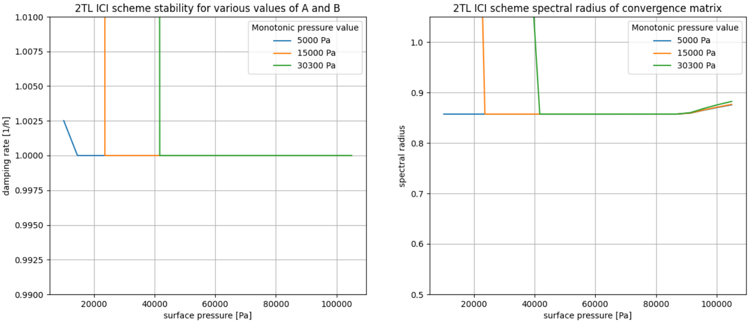

Figure: Growth rate of the most unstable vertical mode (lefft) and spectral radius (convergence speed) if ICI scheme (right). Computed for k=0, dt=120s, SITRA=50K, SITR=350K, SIPR=900hPa.

Analysis of stability - pressure related instabilities

Stability "limit" pressure vs monotonic surface pressure = from lowest surface pressure in model domain the optimal hybrid coordinate can be determined.

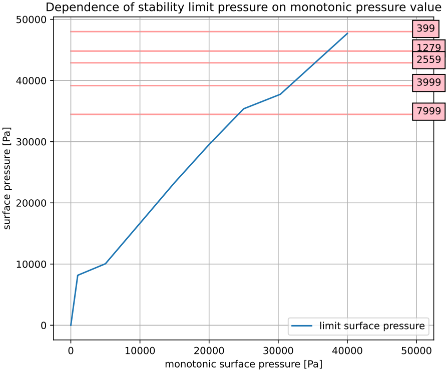

Figure: Surface pressure value where stability suddenly increase. Computed for dx=5km, dt=120s, SITRA=50K, SITR=350K, SIPR=900hPa.

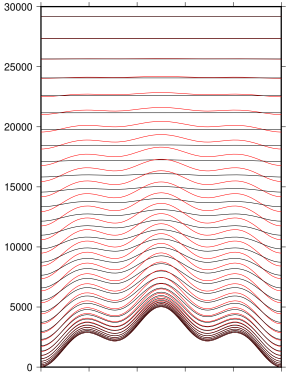

Figure: constant η isolines - operational coordinate in black (303hPa, tco7999 unstable), adjusted coordinate in red (150hPa tco7999 stable)

Analysis of stability - pressure related instabilities

Exponencial damping rate required to compensate instability $-\frac{ln(1/\lambda)}{\Delta t} * 3600$

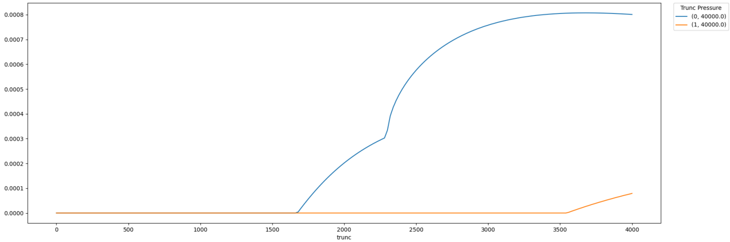

Figure: Growth rate computed for $\overline{\pi_s} = 400hPa$, dt=120s, SITRA=50K, SITR=350K, SIPR=900hPa

Instability is weak and can be compensated by proper design of horizontal diffusion.

Experiment settings

Experiment	Spectral truncation	Grid spacing at the equator
tco1279	1279	7.8km
tco2559	2559	3.9km
tco3999	3999	2.8km
tco7999	7999	1.3km

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Consistent numerics between H and NH model

HY model

$$\frac{\partial q_s}{\partial t} = -\frac{1}{\pi_s}\int_0^1 \vec{\nabla}\,(m\vec{v})\,d\eta$$

$$\frac{dT}{dt} = \frac{\kappa T\omega}{\pi}$$

$$\frac{d\vec{v}}{dt} = -\frac{RT}{\pi}\vec{\nabla}\pi - \vec{\nabla}\phi$$

NH model

$$\frac{\partial q_s}{\partial t} = -\frac{1}{\pi_s}\int_0^1 \vec{\nabla}\,(m\vec{v})\,d\eta$$

$$\frac{dT}{dt} = \frac{\kappa T\omega}{\pi} - \kappa T\left(\frac{\omega}{\pi} + \frac{C_p}{C_v}D_3\right)$$

$$\frac{d\vec{v}}{dt} = -\frac{RT}{\pi}\vec{\nabla}\pi - RT\vec{\nabla}\hat{q} - \vec{\nabla}\phi - \frac{1}{m}\frac{\partial(p-\pi)}{\partial\eta}\vec{\nabla}\phi$$

$$\frac{dgw}{dt} = \frac{g^2}{m}\frac{\partial(p-\pi)}{\partial\eta}$$

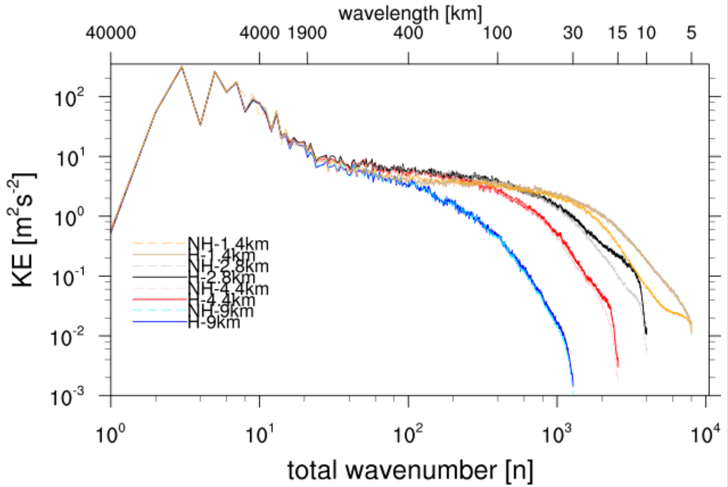
$$\frac{d\hat{q}}{dt} = -\left(\frac{\omega}{\pi} + \frac{C_p}{C_v}D_3\right)$$

Continuity equation

NH model converges towards H model solution when flow is hydrostatic.

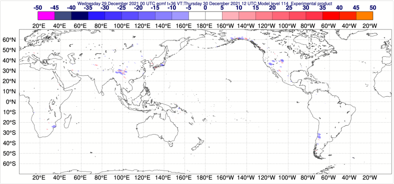
H vs NH

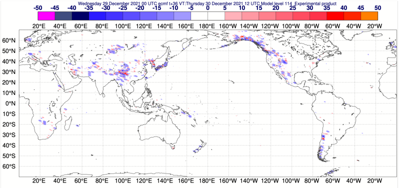
Kinetic energy spectra at 50hPa of H vs NH simulations at tco1279, tco2559, tco3999 and tco7999. Differences for waves < 20km. Where this diffs happens ?

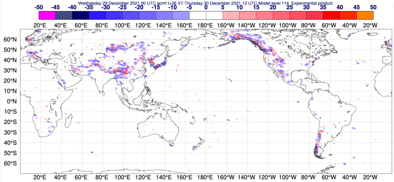


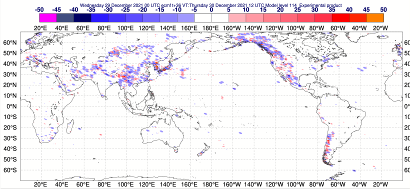
H vs NH

Pressure departure field at 850hPa.



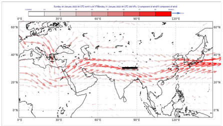




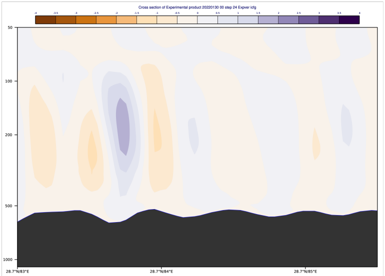


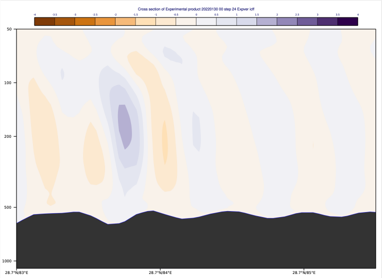
H vs NH - Himalaya jet stream

30.1.2022 : Vertical cross section of w +24h.



TCo1279





H vs NH - Himalaya jet stream

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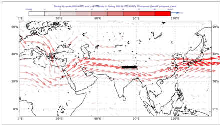
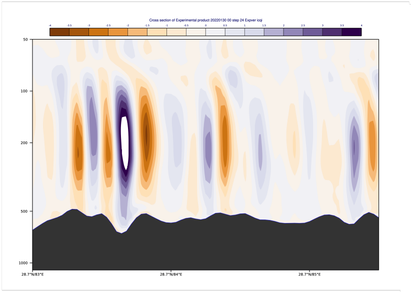
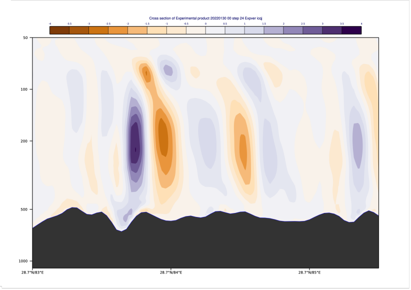


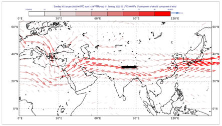
TCo2559



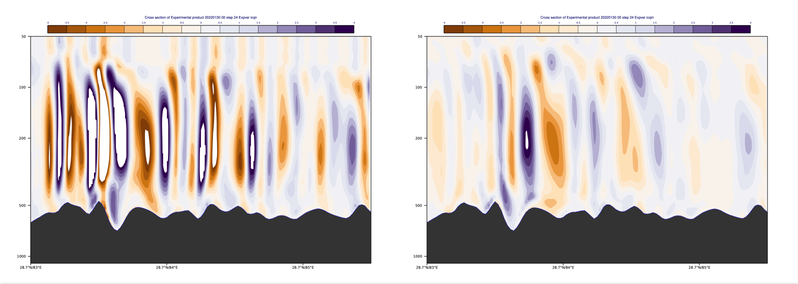


H vs NH - Himalaya jet stream

30.1.2022 : Vertical cross section of w +24h.

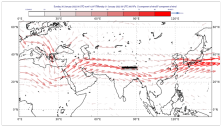


TCo3999

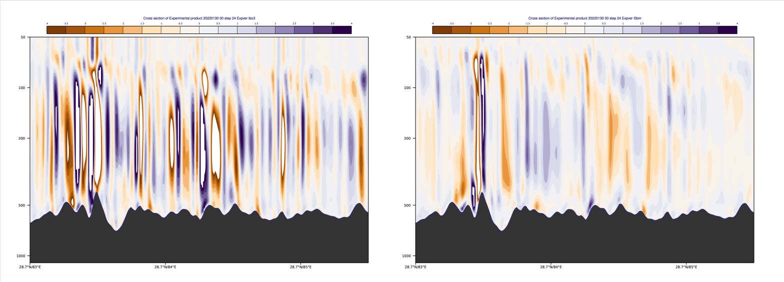


H vs NH - Himalaya jet stream

30.1.2022 : Vertical cross section of w +24h.



TCo7999

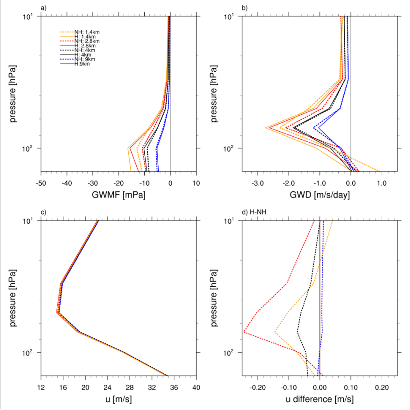


H vs NH

Zonal mean gravity waves diagnostic based on budget equation (Polichtchouk, 2022):

$$\bar{u}_t = \bar{v}^*[f - (a\cos\phi)^{-1}(\bar{u}\cos\phi)_\phi] - \bar{w}^*\bar{u}_z + (\rho a\cos\phi)^{-1}\nabla\cdot\mathbf{F} + \rho^{-1}(\rho\overline{u'w'})_z + X$$

diagnosed assuming $kms < \lambda_g < 1900km$.



H vs NH

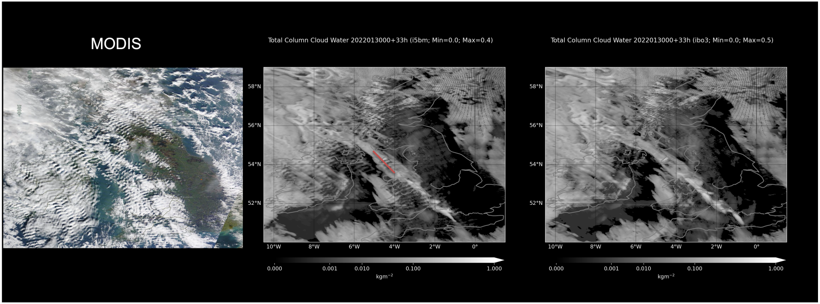


Figure: tco7999 - trapped waves above UK, NH vs HY simulation at tco7999 resolution

H vs NH

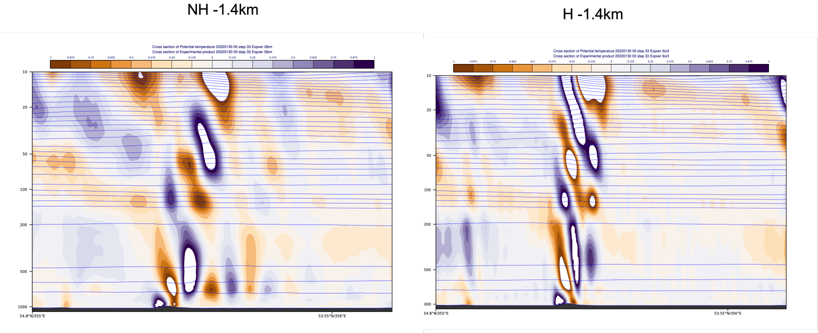
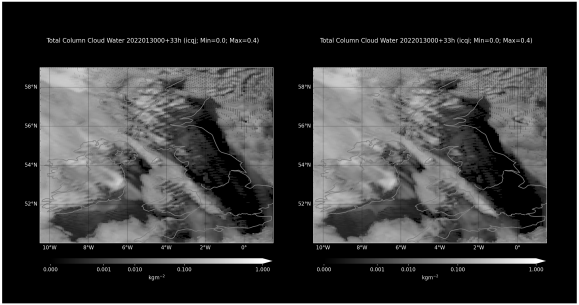


Figure: tco7999 - trapped waves above UK, NH vs HY simulation at tco7999 resolution

H vs NH



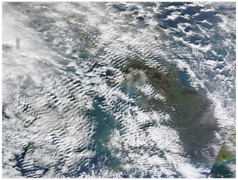


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Figure: tco2559 - trapped waves above UK, NH vs HY simulation at tco2559 resolution