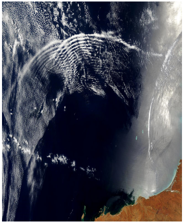
Model development theme: specification of resolved-scale and sub-grid-scale orography, and its effect on climate simulation

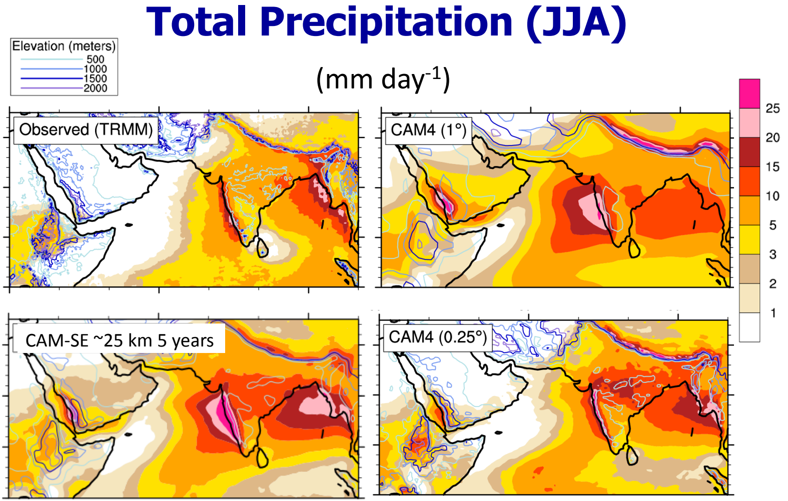
Peter Hjort Lauritzen

Atmospheric Modeling & Predictability Section
Climate & Global Dynamics Division
NCAR Earth System Laboratory
National Center for Atmospheric Research (NCAR), Boulder, Colorado


Lecture at Summer school: *Introduction to Climate Modeling* (University of Stockholm)

Picture source: www.weathervortex.com/sky-ribbons.htm



Courtesy Rich Neale

Initial implementation of CAM-SE uses very smooth topography.
Reduces improvement in precipitation patterns related to topography

Why did we revisit topography specification in CAM?

Current default topography generation software is based on regular latitude-longitude grids
$\rightarrow$ no direct support for new grids
(cubed-sphere, Voronoi/Icosahedral, unstructured, ...)

Some physical ‘inconsistencies’ were found in the way the sub-grid-scale variables were computed

$\Rightarrow$I decided to totally rewrite the topography generation software! (end of last year)

Outline

1. 'Definition' of internal gravity waves in the atmosphere
2. 'Energy' spectra of orography
3. Resolved-scale orography in CAM
   - 'Raw' data → CAM grid ('resolved-scale' variables)
   - Smoothing of elevation data
   - Smoothing and precipitation
4. Sub-grid scale orography
   - Small-scale orographic processes
   - Linear theory of orographic gravity waves and momentum flux
   - 'Raw' data → CAM grid ('sub-grid-scale' variables)
5. Effect of new sub-grid-scale orographic specification on climate simulation

‘Definition’ of internal gravity waves in the atmosphere

Internal gravity waves are an essential part of (among other processes) orographic effects and they are a major mechanism for the transfer of momentum

Gravity waves can only exist in stably stratified fluid, i.e. Brunt-Väisälä frequency

$$N^2 = \sqrt{\frac{g}{\theta}\frac{d\theta}{dz}} > 0, \tag{1}$$

where θ potential temperature.

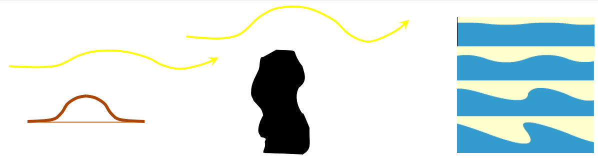
If an air parcel is displaced vertically away from equilibrium its equilibrium experiences a vertical acceleration back towards its initial position - buoyancy force!

Gravity waves are waves where the restoring force is buoyancy
(so, loosely speaking, there is a balance between the Earth pulling down and buoyancy of the atmosphere pushing up).

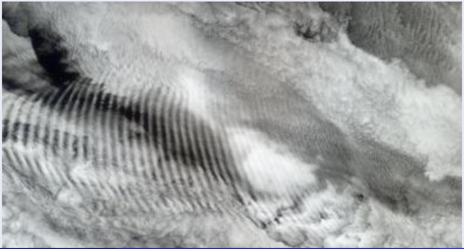
'Definition' of internal gravity waves in the atmosphere

Sources of gravity waves ('they are everywhere'!)

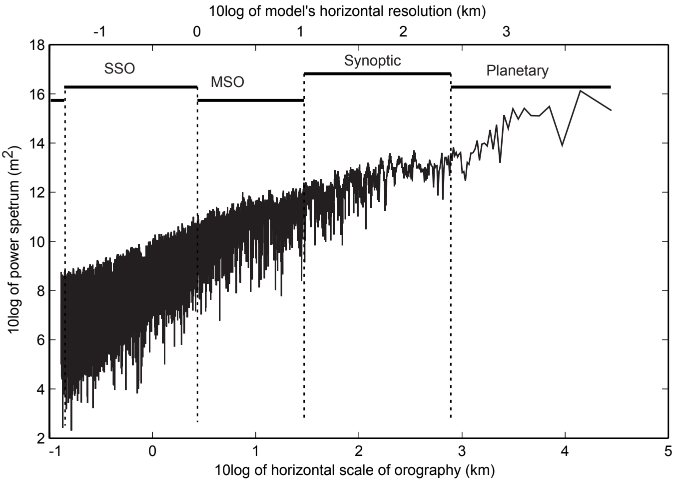
flow over orography, flow over convective cloud, Kelvin-Helmholtz instability, geostrophic adjustment, ...



Gravity waves are sometimes visible thanks to clouds
(when water vapor saturates in the regions where air is ascending due to gravity wave)



Power spectrum of 1D cross section at 45°N



Energy at all scales (down to the scale of the data) - no spectral gap!

From Rontu (2007)

Mountain-related atmospheric processes

Scale	Orographic phenomena	Time scale	Horizontal scale	Essential dynamics
Planetary	Planetary waves	Weeks	1000 - 10000 km	barotropic, hydrostatic conservation of absolute vorticity
Synoptic	Cyclo- and frontogenesis Large-scale precipitation Orographic lift	Days	100 - 1000 km	baroclinic quasi-geostrophic, hydrostatic conservation of potential vorticity
Meso	Buoyancy waves and blocking[1] Local (thermal) circulations Orographic convection Fog and low clouds	Hours - Day	1 - 100 km	[1]stable stratification hydrostatic → nonhydrostatic rotating → nonrotating directional effects
Small Micro	Turbulent eddies	Minutes - Hours	100 m - 1 km 10 m	non-hydrostatic non-rotating isotropic

From Rontu (2007)

CAM elevation-related input variables

csm\inputdata\atm\cam\topo\USGS-gtopo30-dycore-resolution.nc

'Resolved-scale' variables:

- PHIS: Surface geopotential (elevation over sea-level $\times$ g); we assume g is constant and assume that Earth is a sphere.
- LANDFRAC: Land fraction (fraction of grid cell covered with land; LANDFRAC$\in [0:1]$)

Sub-grid-scale variables:

- SGH30: Standard deviation of elevation on scales approximately less than 3-6km
- SGH: Standard deviation of elevation on scales approximately larger than 3-6km and less than the grid-scale.

Why SGH and SGH30?

For the parameterization of **SOME** atmospheric processes associated with orography that we can not explicitly resolve.

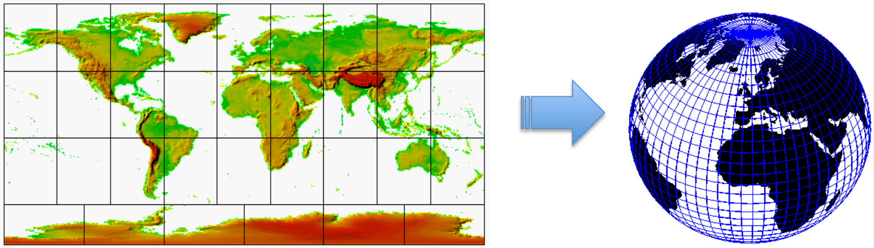
(I'll return to this in just a moment)

Resolved-scale orography: PHIS

Where do we get elevation data from?

GTOPO30: a global digital elevation model with a horizontal grid spacing of 30 arc seconds (approximately 1 kilometer) compiled by USGS (U.S. Geological Survey).
Contains elevation in meters and ocean/land mask (binary: 0 or 1).

Stored in 33 tiles in binary format



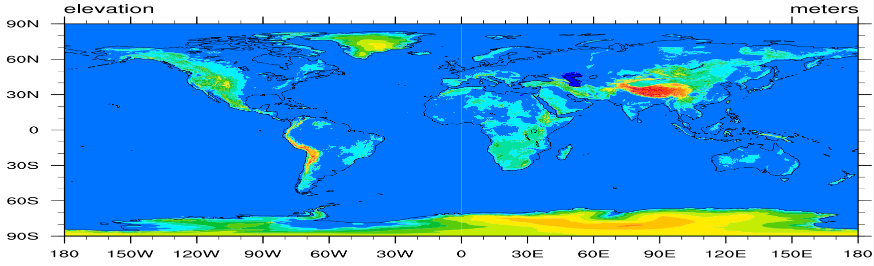
First step: convert data to a single NetCDF format file
(7.5GB; elevation and landfraction stored in integer format)

http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/gtopo30_info

Where do we get elevation data from?

GTOPO30: a global digital elevation model with a horizontal grid spacing of 30 arc seconds (approximately 1 kilometer) compiled by USGS (U.S. Geological Survey).
Contains elevation in meters and ocean/land mask (binary: 0 or 1).

Stored in 33 tiles in binary format



First step: convert data to a single NetCDF format file
(7.5GB; elevation and landfraction stored in integer format)

http://eros.usgs.gov/#/Find_Data/Products_and_Data_Available/gtopo30_info

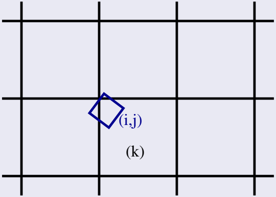
Resolved-scale orography: PHIS

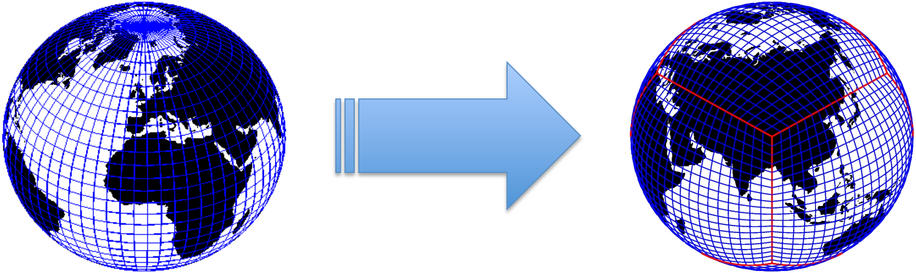
Intermediate grid (gnomonic cubed-sphere grid of approximately 3km resolution)

For reasons that will become clear (in a moment) we transfer data to an intermediate grid

The transfer is done by the process of binning, that is, if the center of 'USGS grid cell' (i, j) is located in intermediate grid cell k, the information in source grid cell (i, j) is assigned to intermediate grid cell k.

Accurate as long as $\Delta x_{intermediate} >> \Delta x_{USGS}$

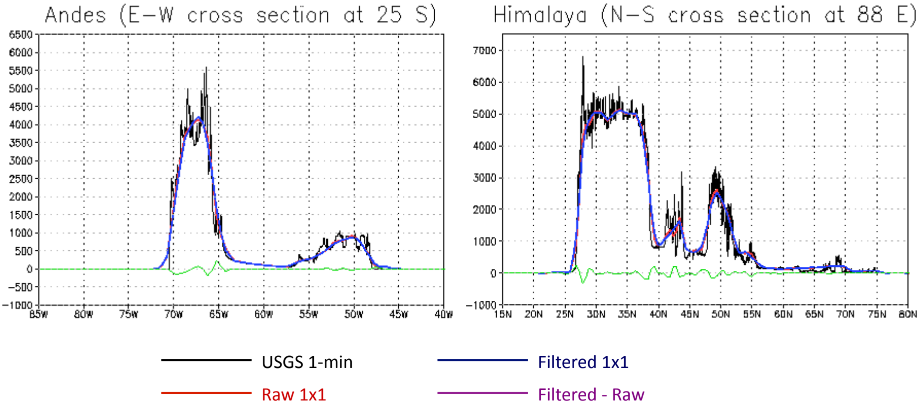




Resolved-scale orography: PHIS

Intermediate grid (gnomonic cubed-sphere grid of approximately 3km resolution)

For reasons that will become clear (in a moment) we transfer data to an intermediate grid



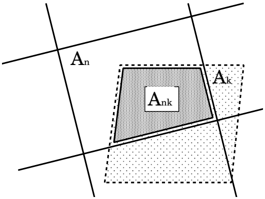
Binning is a ‘smoothing’ step

Figure is from S.J. Lin (GFDL) and applies to their modeling system

Resolved-scale orography: PHIS

Intermediate grid to target grid

The information is transferred from intermediate grid to any target grid (lat-lon, cubed-sphere, icosahedral/Voronoi, unstructured) via rigorous remapping (volume conserving)

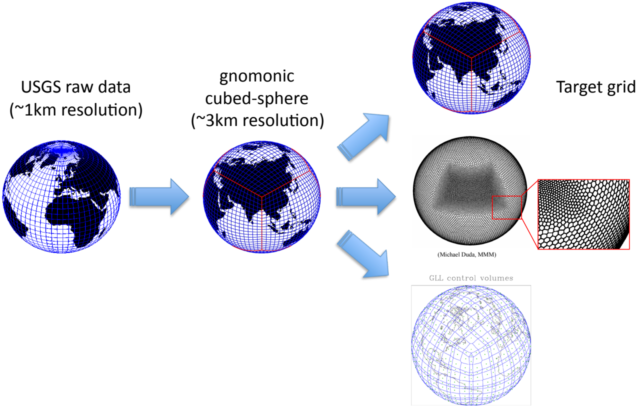


This is done using technology developed over the past 4 years (Lauritzen and Nair, 2008; Ullrich et al., 2009; Lauritzen et al., 2010):

- search for overlap areas (a non-trivial problem, in particular, in spherical geometry)!
- area integrals are performed by converting them into line-integrals using the divergence theorem in gnomonic cubed-sphere coordinates (has some nice properties: line-integrals along gnomonic iso-lines can be performed analytically on the sphere)

Intermediate grid to target grid

The information is transferred from intermediate grid to any target grid (lat-lon, cubed-sphere, icosahedral/Voronoi, unstructured) via rigorous remapping (volume conserving)



We now have accurate volume conserving cell-average values of PHIS on the target grid

PHIS smoothing?

No smoothing of PHIS

Although the binning process smoothes PHIS significantly it is not sufficient

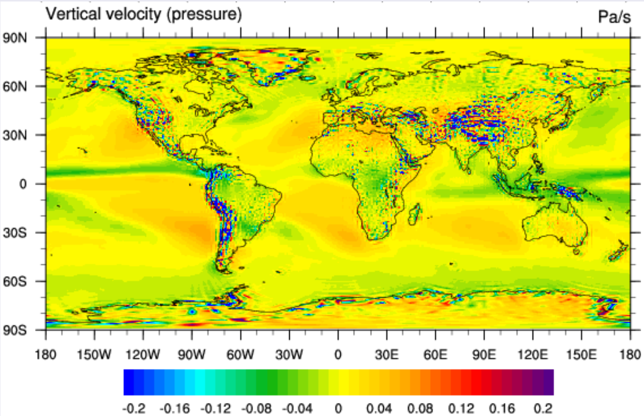


Figure courtesy of Mark Taylor (Sandia)

Figure: 5 year averaged 500hPa vertical pressure velocity $\omega = \frac{dp}{dt}$ for CAM-SE using (almost) unsmoothed PHIS. Excessive generation of gravity waves contaminates the solution

Some smoothing of PHIS is necessary

Smoothing of PHIS is necessary for many dynamical cores - how and how much smoothing that is needed is a 'grey' area of climate modeling and it is usually highly dependent on the internal diffusion properties of the numerical method used by the dynamical core as well as the strength of external diffusion operators (e.g., hyperdiffusion operators ∇^4).

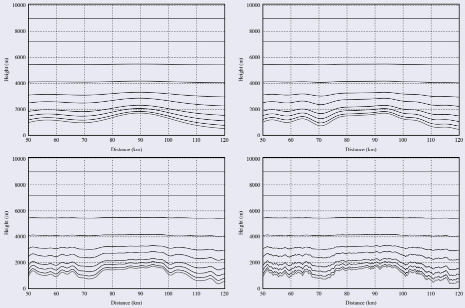


FIGURE 3.3. Hypothetic vertical coordinate based on Carpathian profiles (smoothing to the resolution of 32 km, 10 km, 3.3m and raw data, see Fig. 3.2). A section from 50 km to 120 km of the profile in Fig. 3.1 is shown.

Figure from Rontu (2007)

PHIS smoothing and precipitation

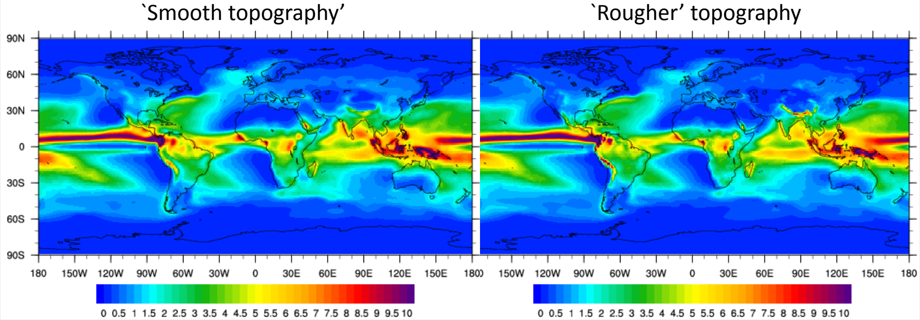


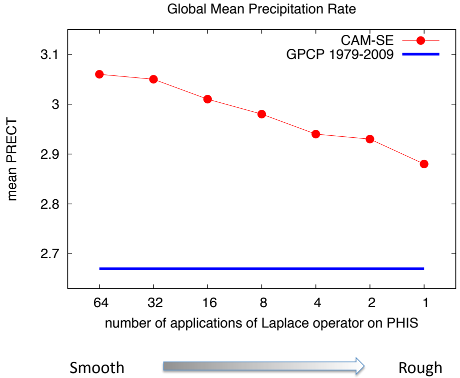
Figure: 5 year mean for precipitation for CAM-SE using very smooth PHIS (left) and rougher PHIS (right), respectively.

Figure courtesy of Mark Taylor (Sandia)

Delicate 'balance' between smoothing of PHIS and diffusive properties of the dynamical core!

PHIS smoothing?

PHIS smoothing and precipitation



Note that the simulations with rougher topography are ‘useless’!!!

WARNING

This also illustrates the danger of using just one diagnostic to ‘tune’ parameters ...

PHIS smoothing?

That is all I will say on resolved-scale topography
(work ongoing on optimal smoothing of topography for CAM-SE)

$\rightarrow$ now to the unresolved scales ...

Orography can generate a wide range of sub-grid-scale processes that can influence the 'resolved-scale' flow

1. Blocking

The formation of a blocked zone upstream of the mountain with weak velocities.

⇒ can generate upward propagating gravity waves that influence the large-scale flow

2. Flow deviated

Upstream of blocking zone the low-level flow splits into two branches.

⇒ low-level flow flows around and not over the mountain

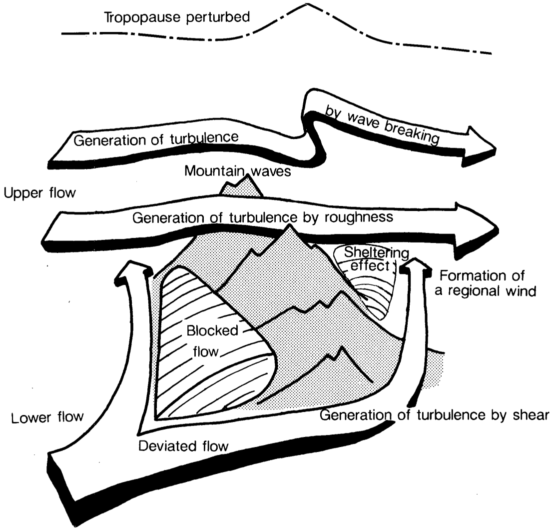


Figure from Bougeault et al. (1990)

Orography can generate a wide range of sub-grid-scale processes that can influence the 'resolved-scale' flow

3. Generation of turbulence by shear

On the lateral edges of the mountain, the deviation results in flow with strong curvature in the lower levels and less perturbed flow aloft.

⇒ significant wind shear through deep layer (with complex 3D structure)

⇒ turbulence and vertical transfer of momentum

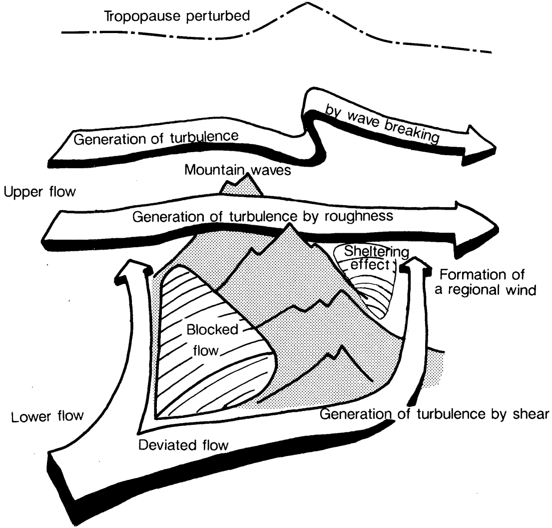


Figure from Bougeault et al. (1990)

Orography can generate a wide range of sub-grid-scale processes that can influence the 'resolved-scale' flow

4. Regional wind

Depending on stability, the low-level flow may be accelerated to form a well-defined regional wind either upstream or downstream of the mountain.

⇒ strong decoupling of boundary layer (usually capped by a strong inversion) and free atmosphere

⇒ exchange of momentum by turbulence through the inversion

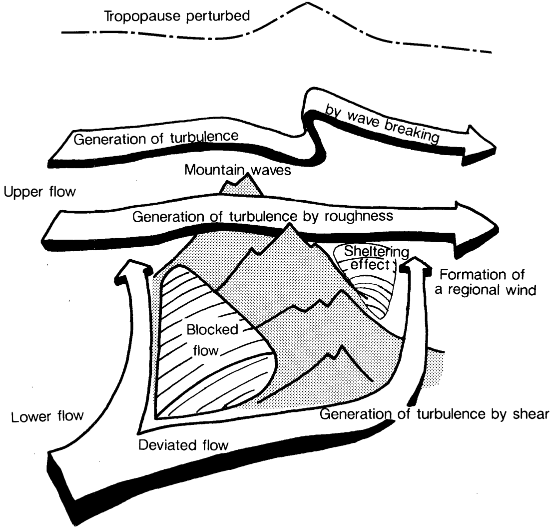


Figure from Bougeault et al. (1990)

Orography can generate a wide range of sub-grid-scale processes that can influence the ‘resolved-scale’ flow

5. Generation of turbulence by roughness

Flow is accelerated above the ridge

⇒ dynamic boundary layer is formed with strong low-level turbulence

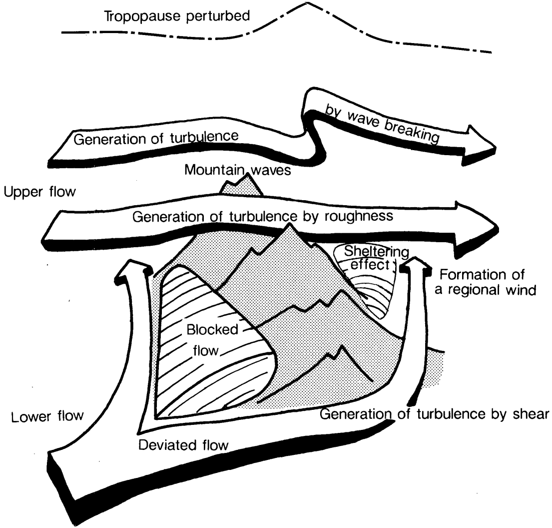


Figure from Bougeault et al. (1990)

Orography can generate a wide range of sub-grid-scale processes that can influence the 'resolved-scale' flow

6. Mountain wave breaking

Gravity waves are generated by central part of the mountain

⇒ they transfer momentum vertically and may break, resulting in turbulence and strong downslope wind formation

⇒ significant deformation of tropopause above main ridge

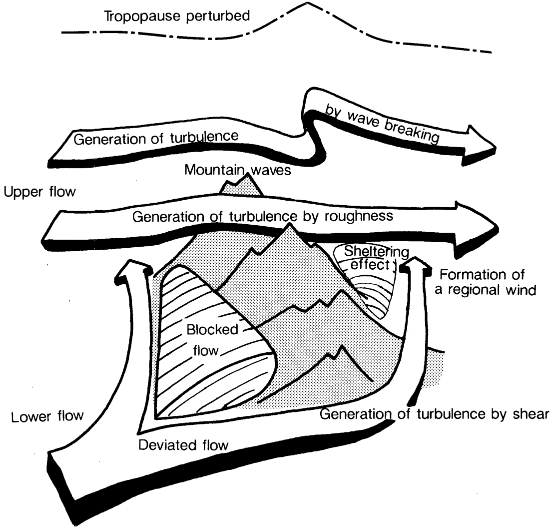


Figure from Bougeault et al. (1990)

Orography can generate a wide range of sub-grid-scale processes that can influence the 'resolved-scale' flow

7. Sheltering effect

Zone of weak, low-level wind is often present immediately downstream of the main ridge, as a result of a sheltering effect.

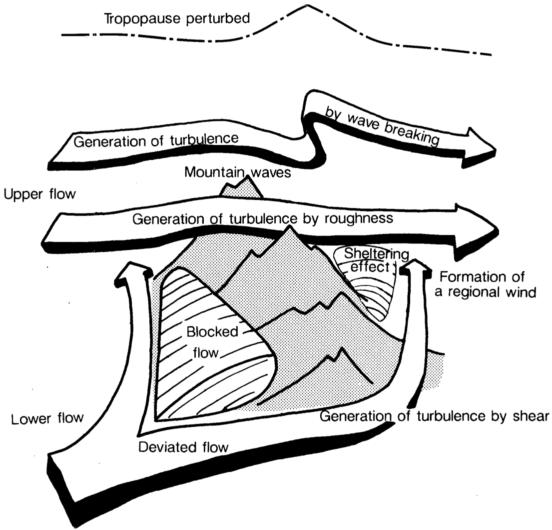


Figure from Bougeault et al. (1990)

Orography can generate a wide range of sub-grid-scale processes that can influence the 'resolved-scale' flow

What do we attempt to parameterize in CAM?

- Vertically propagating gravity waves that affect the large-scale flow (through momentum deposition) - **Gravity wave drag** (GWD)
- Turbulence generated by orography that affect the large-scale flow - **Turbulent Mountain Stress** (TMS)
- no explicit parameterization of blocking, sheltering, flow splitting, etc.

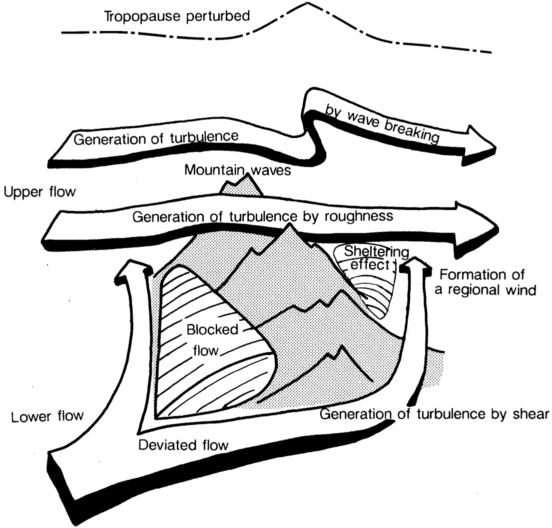


Figure from Bougeault et al. (1990)

Orography can generate a wide range of sub-grid-scale processes that can influence the 'resolved-scale' flow

How do we relate sub-grid-scale elevation data to vertically propagating gravity waves as well as turbulence that affects the large-scale flow?

Lets start with gravity waves and ask more specifically:

- is there a relation between the scale of the mountain and the vertically propagating gravity waves?

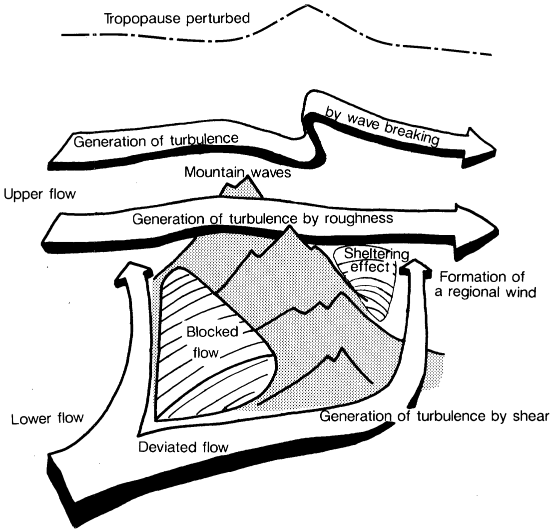


Figure from Bougeault et al. (1990)

Linear theory for topographic waves (Holton, 2004) - infinite periodic mountain range

When do gravity waves propagate in the vertical? (infinite mountain range)

Equations: $x - z$ plane, no rotation (horizontal wavelengths of interest smaller than about 100 km), Boussinesq approximation (density constant except for buoyancy term in vertical momentum equation)

Method: linearize equations about basic state $\mathrm{U}(z)$, decompose into Fourier components and solve the system analytically for a steady-state solution

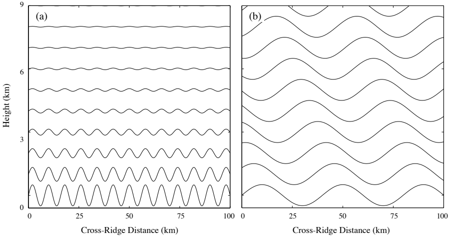


Figure 1: Streamlines in steady airflow over an infinite series of sinusoidal ridges when $N = .01\ \mathrm{s}^{-1}$, $U = 15\ \mathrm{ms}^{-1}$, and the wavelength of the topography is (a) 8 km (case $Uk > N$) or (b) 40 km (case $Uk < N$). The flow is from left to right. The lowest streamline coincides with the topography.

Figure courtesy of Dale Durran (University of Washington)

Linear theory for topographic waves (Holton, 2004) - infinite periodic mountain range

When do gravity waves propagate in the vertical? (infinite mountain range)

Stability (N) constant, topography scale (expressed in terms of wave number: $k = 2\pi/L$), and mean wind speed (U) determine if gravity waves propagate in the vertical or not:

$$\frac{Uk}{N} > 1 \Rightarrow \text{no vertical propagation} \quad \frac{Uk}{N} < 1 \Rightarrow \text{vertical propagation} \tag{1}$$

$N = 0.01 s^{-1}$, $U = 15 m s^{-1}$ $\Rightarrow$ $\frac{Uk}{N} = 1$ for L≈9 km

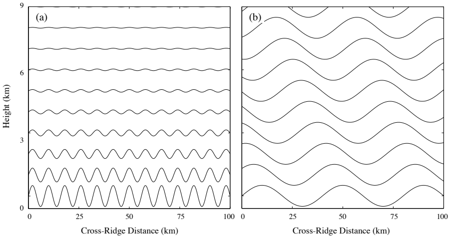


Figure 1: Streamlines in steady airflow over an infinite series of sinusoidal ridges when $N = .01\ s^{-1}$, $U = 15\ ms^{-1}$, and the wavelength of the topography is (a) 8 km (case $Uk > N$) or (b) 40 km (case $Uk < N$). The flow is from left to right. The lowest streamline coincides with the topography.

Figure courtesy of Dale Durran (University of Washington)

Linear theory for topographic waves (Holton, 2004) - infinite periodic mountain range

Let me dwell on this a little bit more ...

Critical parameter:

$$\frac{U}{L\,N} < \frac{1}{2\pi} \quad \text{vertical propagation} \qquad \frac{U}{L\,N} > \frac{1}{2\pi} \quad \text{exponential decay in the vertical} \qquad (1)$$

So what favors vertically propagating gravity waves?

- Wider or narrower mountains?

Linear theory for topographic waves (Holton, 2004) - infinite periodic mountain range

Let me dwell on this a little bit more ...

Critical parameter:

$$\frac{\mathrm{U}}{\mathrm{L}\,\mathrm{N}} < \frac{1}{2\pi} \quad \text{vertical propagation} \qquad \frac{\mathrm{U}}{\mathrm{L}\,\mathrm{N}} > \frac{1}{2\pi} \quad \text{exponential decay in the vertical} \tag{1}$$

So what favors vertically propagating gravity waves?

- Wider or narrower mountains?
- (answer) wider mountains (L increases $\Rightarrow \frac{\mathrm{U}}{\mathrm{L}\,\mathrm{N}}$ decreases)

Linear theory for topographic waves (Holton, 2004) - infinite periodic mountain range

Let me dwell on this a little bit more ...

Critical parameter:

$$\frac{\mathrm{U}}{\mathrm{L}\,\mathrm{N}} < \frac{1}{2\pi} \quad \text{vertical propagation} \qquad \frac{\mathrm{U}}{\mathrm{L}\,\mathrm{N}} > \frac{1}{2\pi} \quad \text{exponential decay in the vertical} \tag{1}$$

So what favors vertically propagating gravity waves?

- Wider or narrower mountains?
- (answer) wider mountains (L increases $\Rightarrow \frac{\mathrm{U}}{\mathrm{L}\,\mathrm{N}}$ decreases)
- Faster or slower wind speeds?

Linear theory for topographic waves (Holton, 2004) - infinite periodic mountain range

Let me dwell on this a little bit more ...

Critical parameter:

$$\frac{U}{L\,N} < \frac{1}{2\pi} \quad \text{vertical propagation} \qquad \frac{U}{L\,N} > \frac{1}{2\pi} \quad \text{exponential decay in the vertical} \tag{1}$$

So what favors vertically propagating gravity waves?

- Wider or narrower mountains?
- (answer) wider mountains (L increases $\Rightarrow \frac{U}{L\,N}$ decreases)
- Faster or slower wind speeds?
- (answer) slower wind speeds (U decreases $\Rightarrow \frac{U}{L\,N}$ decreases)

Linear theory for topographic waves (Holton, 2004) - infinite periodic mountain range

Let me dwell on this a little bit more ...

Critical parameter:

$$\frac{U}{LN} < \frac{1}{2\pi} \quad \text{vertical propagation} \qquad \frac{U}{LN} > \frac{1}{2\pi} \quad \text{exponential decay in the vertical} \tag{1}$$

So what favors vertically propagating gravity waves?

- Wider or narrower mountains?
- (answer) wider mountains (L increases $\Rightarrow \frac{U}{LN}$ decreases)
- Faster or slower wind speeds?
- (answer) slower wind speeds (U decreases $\Rightarrow \frac{U}{LN}$ decreases)
- More or less stable stratification?

Linear theory for topographic waves (Holton, 2004) - infinite periodic mountain range

Let me dwell on this a little bit more ...

Critical parameter:

$$\frac{U}{L\,N} < \frac{1}{2\pi} \quad \text{vertical propagation} \qquad \frac{U}{L\,N} > \frac{1}{2\pi} \quad \text{exponential decay in the vertical} \tag{1}$$

So what favors vertically propagating gravity waves?

- Wider or narrower mountains?
- (answer) wider mountains (L increases $\Rightarrow \frac{U}{L\,N}$ decreases)
- Faster or slower wind speeds?
- (answer) slower wind speeds (U decreases $\Rightarrow \frac{U}{L\,N}$ decreases)
- More or less stable stratification?
- (answer) more stable (N increases $\Rightarrow \frac{U}{L\,N}$ decreases)

Linear theory for topographic waves (Holton, 2004) - infinite periodic mountain range

Let me dwell on this a little bit more ...

Critical parameter:

$$\frac{U}{L\,N} < \frac{1}{2\pi} \quad \text{vertical propagation} \qquad \frac{U}{L\,N} > \frac{1}{2\pi} \quad \text{exponential decay in the vertical} \tag{1}$$

So what favors vertically propagating gravity waves?

- Wider or narrower mountains?
- (answer) wider mountains (L increases $\Rightarrow \frac{U}{L\,N}$ decreases)
- Faster or slower wind speeds?
- (answer) slower wind speeds (U decreases $\Rightarrow \frac{U}{L\,N}$ decreases)
- More or less stable stratification?
- (answer) more stable (N increases $\Rightarrow \frac{U}{L\,N}$ decreases)

Next

Obviously mountains are not sinusoidal shaped so what happens if we consider flow over an isolated 2D mountain?

When do gravity waves propagate in the vertical? (isolated mountain)

Changes solution significantly (solution computed numerically but it is close to predictions by linear theory):

- (left Figure) $\frac{\mathrm{U}}{\mathrm{L\,N}} << 1$ so gravity waves propagate in the vertical; energetic mountain waves are found only in region directly above the mountain (in the non-linear non-hydrostatic solution some waves do appear downstream)!

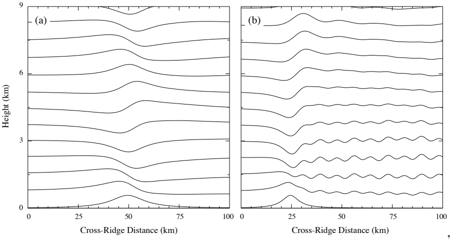


Figure 2: Streamlines in steady airflow over an isolated mountain as predicted by linear theory when (a) $a = 10$ km, N is constant, and $Nh_0/U = 0.6$; (b) $a = 5$ km, N is constant throughout each of two layers such that between the surface and 3 km $N_L h_0/U = 0.6$, and above 3 km $N_U h_0/U = 0.24$.

Figure courtesy of Dale Durran (University of Washington)

When do gravity waves propagate in the vertical? (isolated mountain)

Changes solution significantly (solution computed numerically but it is close to predictions by linear theory):

- (right Figure) Contrary to before N has a different (but constant value) above 3km and mountain is narrower ⇒ trapped Lee waves (resonant Lee wave) extending downstream from the ridge throughout the layer

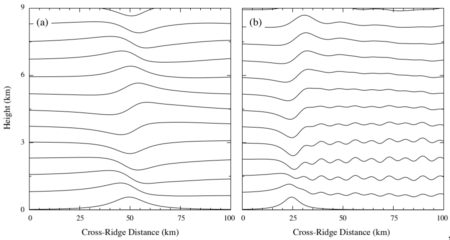


Figure 2: Streamlines in steady airflow over an isolated mountain as predicted by linear theory when (a) $a = 10$ km, N is constant, and $Nh_0/U = 0.6$; (b) $a = 5$ km, N is constant throughout each of two layers such that between the surface and 3 km $N_L h_0/U = 0.6$, and above 3 km $N_U h_0/U = 0.24$.

Figure courtesy of Dale Durran (University of Washington)

Conditions for trapped Lee waves is more complicated

Vertical variations in U and N such that Scorer parameter

$$\ell^2 = \frac{N^2}{U^2} - \frac{1}{U}\frac{d^2U}{dz^2}, \tag{2}$$

decreases significantly with height ⇒ cross-ridge flow may generate qualitatively different wave (i.e. trapped Lee wave)

Non-linear topographic waves

Nonlinear (non-hydrostatic) solution to the same problem

- Compared to linear solution: gradients increase and 'more resonance' in the trapped Lee waves
- Vertically propagating wave: despite the modest differences in the shape of the streamlines in the linear and nonlinear waves, the amplitude is almost identical!
- → the GWD parameterization in CAM is based on this linear theory.

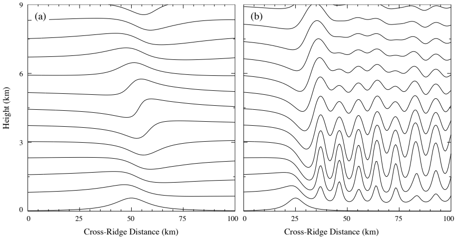


Figure 3: As in Figure 2 except that the streamlines are for a fully nonlinear flow as computed using a numerical model. The trapped waves in panel b are not completely steady; the solution is shown a nondimensional time $Ut/a = 20$ after starting the flow from rest.

Figure courtesy of Dale Durran (University of Washington)

Vertical momentum transport

Vertically propagating gravity waves

- $\Rightarrow$ region of high pressure upstream of ridge crest and low pressure in the lee (see spacing of streamlines)
- $\Rightarrow$ asymetry in pressure distribution across ridge
- $\Rightarrow$ force exerted on the mean flow by the topography

Mean flow ($\overline{U}$, $\overline{\omega} = 0$) is slowed down by vertically propagating gravity waves:

$$\frac{\partial \rho_0 \overline{u}}{\partial t} = -\frac{\partial}{\partial z}\left(\rho_0 \overline{u' \, \omega'}\right) \tag{3}$$

where u' and ω' are perturbations about the mean flow.

For steady, inviscid, small-amplitude waves $\rho_0 \overline{u' \, \omega'}$ = constant except at critical level (Eliassen-Palm)

Mountain waves are also dissipated through:

- wave breaking and overturning if they attain sufficiently large amplitude due to decrease in density with height
- if they propagate into regions where N/U increases significantly

Vertical momentum transport

Observed momentum flux

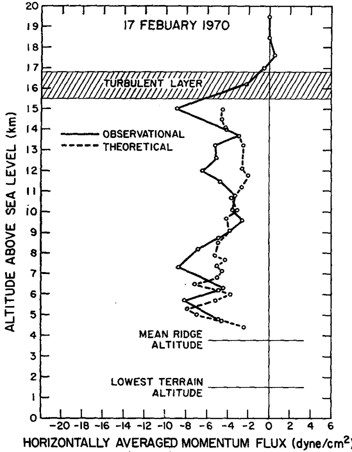


FIG. 14. Mean observed profile of momentum flux obtained by averaging the three curves shown in Fig. 13 (solid line). The computed profile of momentum flux derived from integration of Eqs. (5.7)–(5.9) is shown as the dashed line.

Figure from Lilly and Kennedy (1973)

CAM separation of scales for sub-grid-scale orography

SGH and SGH30

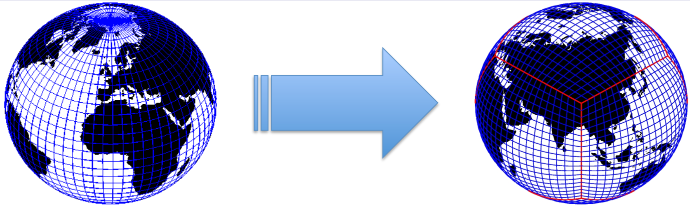
- $\mathrm{L} > 3\mathrm{km}$ $\Rightarrow$ vertically propagating gravity waves possible (linear theory) $\Rightarrow$ transport of momentum between source and regions where they are dissipated or absorbed (gravity wave drag)
- $\mathrm{L} < 3\mathrm{km}$ $\Rightarrow$ no vertically propagating gravity waves (linear theory), however $\Rightarrow$ turbulent processes that exert a form drag on the large scale flow (turbulent mountain stress)

Isotropic separation of sub-grid-scales

SGH30 for turbulent mountain stress (TMS) parameterization

Standard deviation of elevation on scales smaller than approximately 3-6 km

That is why we use the intermediate 3 km cubed-sphere grid (which is quasi-isotropic):



Standard deviation of 1km USGS raw data and 3km cubed-sphere 'area-averaged' (binned) elevation in cubed-sphere cell k

$$\text{SGH30}_k = \sqrt{\frac{1}{\Delta A_k} \sum_{(i,j)\in\mathcal{H}(k)} \left(h_k^{(cube)} - h_{ij}^{(USGS)}\right) \Delta A_{ij}^{(USGS)}}, \tag{3}$$

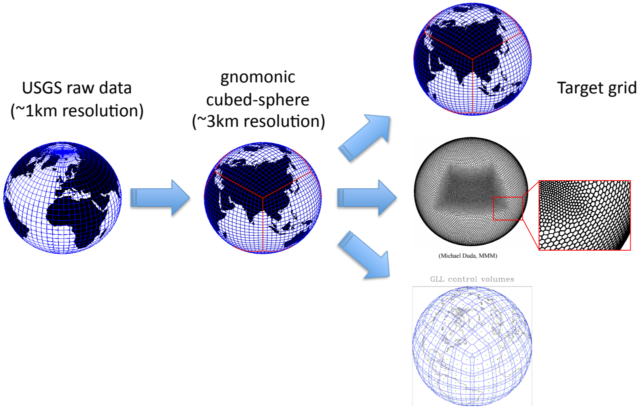
where h is elevation, $\mathcal{H}(k)$ is the set of USGS cell's (i,j) which center points are in cubed-sphere cell k; ΔA are the spherical areas of the respectively cells.

Isotropic separation of sub-grid-scales

SGH for gravity wave drag (GWD) parameterization

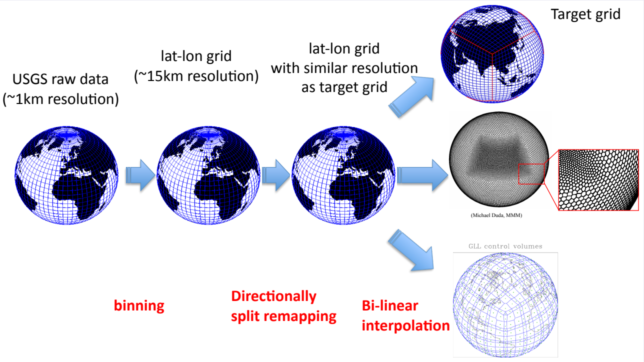
Standard deviation of elevation on scales larger than approximately 3-6 km and less than the target grid scale

SGH computed as SGH30 but variance is between intermediate grid and target grid cell average elevation.



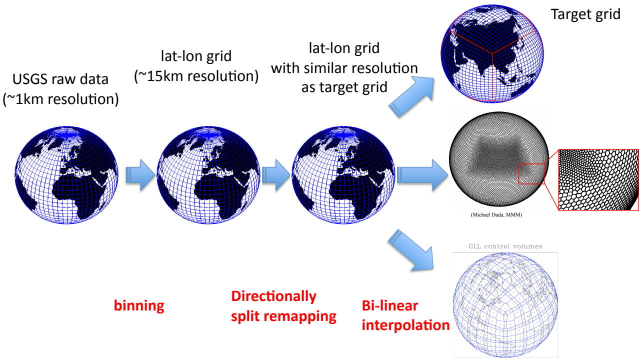
CAM default (CAM5.0) topo software

What I just described is the topography software which is going to be released in the fall to replace the default software (CAM5.0):



Isotropic separation of sub-grid-scales

CAM default (CAM5.0) topo software



Issues

- less isotropic separation of scales (scales separated on a lat-lon grid)!
- not volume conserving (may introduce desirable smoothing)
- extra variance in smoothing of PHIS is not included in SGH

Isotropic separation of sub-grid-scales

'Consistent' SGH30

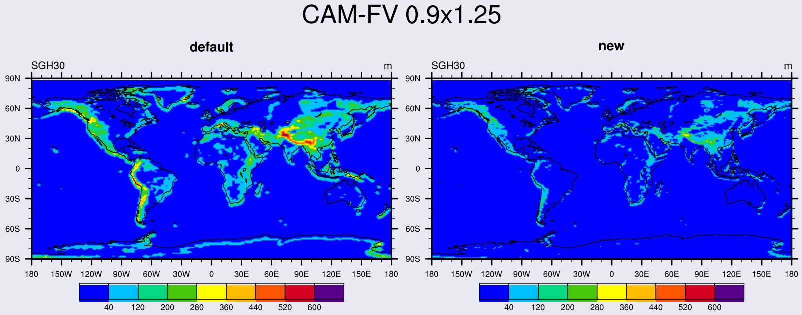
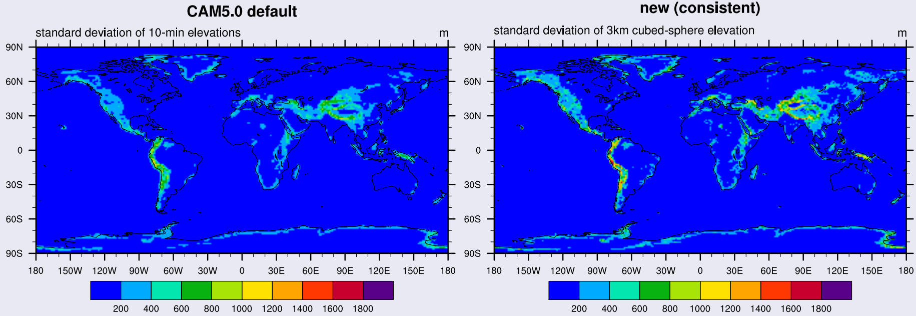


FIG. 11. Raster plot of (a) SGH30 used in CAM5.0 and (b) SGH30 computed 'consistently'.

⇒ much less energy in SGH30
(different cut-off scale and cut-off scale no longer dependent on latitude (isotropic))

'Consistent' SGH

CAM-FV 0.9x1.25

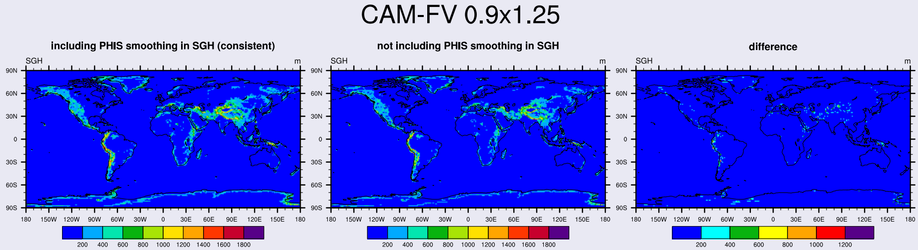


⇒ much more energy in SGH

- different cut-off scale and cut-off scale no longer dependent on latitude (isotropic)
- variance of smoothing PHIS is included in consistent SGH!

Isotropic separation of sub-grid-scales

Effect of PHIS smoothing on SGH



Including the variance introduced by smoothing is locally significant!

Isotropic separation of sub-grid-scales

Experiments

Performed 10 year AMIP-style experiments with CAM-FV based on CAM5 physics.

Resolution: 1 degree

Two runs:

- control (CAM5.0): default topographic files ('inconsistent' SGH and SGH30)
- new: SGH and SGH30 'consistent'

Note that PHIS is the same in both runs so we are isolating the effect of sub-grid-scale specification!

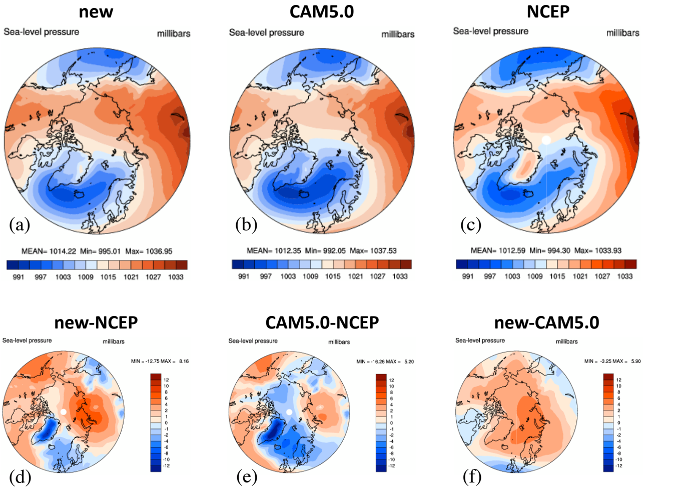
Tuning?

None. Model run with default parameters.

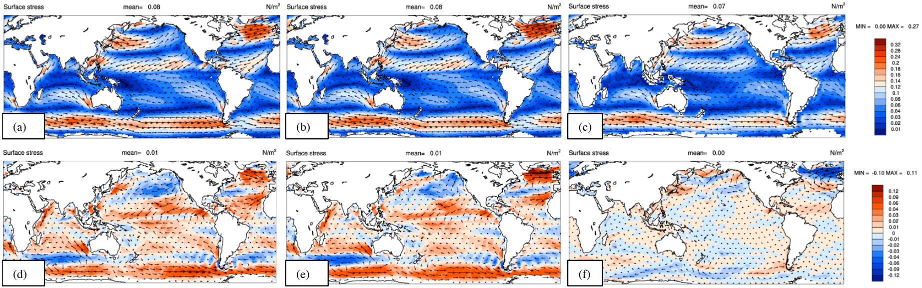
Analysis

AMWG standard diagnostics were run on the data for year 1-10

Sea-level pressure (SLP): effect of SGH and SGH30 (PHIS not altered)



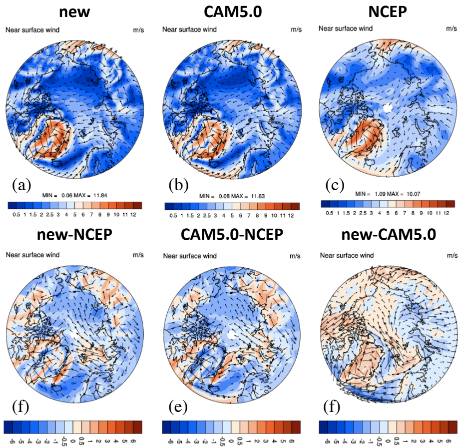
Northern hemisphere winter (December, January, February) sea-level pressure averaged over year 1-10. (a) 'consistent' SGH and SGH30, (b) deault SGH and SGH30. (c) is SLP from the NCAR-NCEP reanalysis data (Kalnay et al., 1996). Second row: difference plots



Same as Figure on previous slide but for surface wind stress.

Wind stress is a very important parameter for air-sea interaction and upper ocean dynamics (Ekman pumping, ...)!

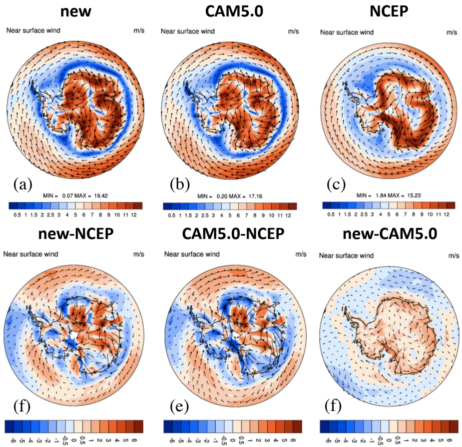
Noticeable improvement in the North-Atlantic



Same as Figure on previous slide but for surface winds (DJF: Northern hemisphere winter).

Surface winds have historically been too weak over Greenland and too strong on the lee side of Greenland → bias reduced!

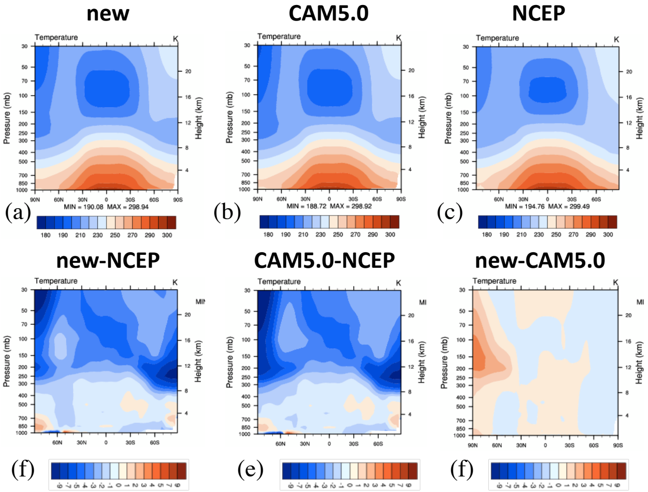
Surface winds: effect of SGH and SGH30 (PHIS not altered)



Same as Figure on previous slide but for Southern hemisphere winter.

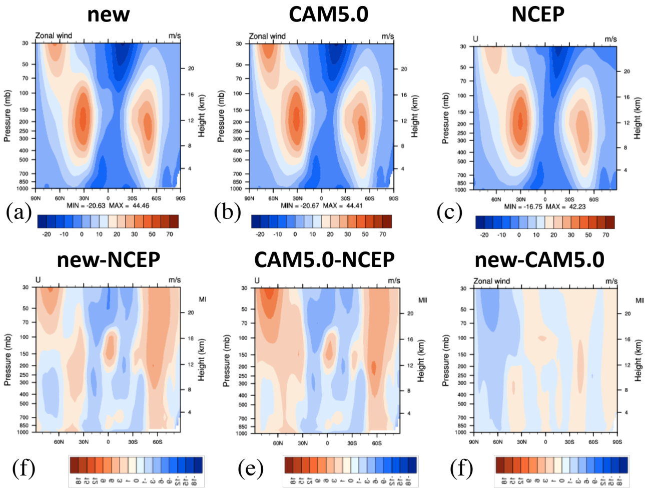
Tendency to underestimate surface winds over land near the periphery of Antarctica - bias has been reduced. Most noticeable are the improvements near the Ross Ice shelf and the Transantarctic Mountain Range.

Zonal temperature: effect of SGH and SGH30 (PHIS not altered)



Same as Figure on previous slide but for zonally averaged temperature.

Cold pole bias (longstanding bias in many climate modes) reduced!



Same as Figure on previous slide but for zonal wind.

Excessive polar night jet during Northern hemisphere winter slowed down!

Ongoing research

Why?

We obviously have more momentum deposition due to vertically propagating gravity waves and less surface drag due to turbulent mountain stress, however, many unanswered questions remain:

- How is the vertical momentum flux altered? Are special synoptic scale situations responsible for the improvement we see? How is tropospheric-stratospheric exchange altered?
- What is the dynamics behind the reduction of the 'cold pole bias'?
- How is the stratospheric circulation altered?
- Is the long-term variability of the climate system altered (e.g., ENSO)?
- ...

More sophisticated parameterizations

- anisotropic GWD
- more advanced TMS parameterization (e.g., ECMWF)
- GWD due to convection
- Blocking
- ...

References

Bougeault, P., Clar, A. J., Benech, B., Carissimo, B., Pelon, J., and Richard, E. (1990). Momentum budget over the pyrénées: The PYREX experiment. *Bull. Amer. Meteor. Soc.*, 71:806–818.

Cariolle, D., Muller, S., and Caylaw, F. (1989). Mountain waves, stratospheric clouds and the ozone depletion over antarctica. *J. Geophys. Res.*, 94(D9):233–11.

Holton, J. R. (2004). *An Introduction to Dynamic Meteorology*. Elsevier Academic Press, Amsterdam, fourth edition edition.

Kalnay, E., Kanamitsu, M., Kistler, R., Collins, W., Deaven, D., Gandin, L., Iredell, M., Saha, S., White, G., Woollen, J., Zhu, Y., Chelliah, M., Ebisuzaki, W., Higgins, W., Janowiak, J., Mo, K., Ropelewski, C., Wang, J., Leetmaa, A., Reynolds, R., Jenne, R., and Joseph, D. (1996). The NCEP/NCAR 40-year reanalysis project. *Bull. Amer. Meteor. Soc.*, 77:437–471.

Lauritzen, P. H. and Nair, R. D. (2008). Monotone and conservative cascade remapping between spherical grids (CaRS): Regular latitude-longitude and cubed-sphere grids. *Mon. Wea. Rev*, 136:1416–1432.

Lauritzen, P. H., Nair, R. D., and Ullrich, P. A. (2010). A conservative semi-Lagrangian multi-tracer transport scheme (CSLAM) on the cubed-sphere grid. *J. Comput. Phys.*, 229:1401–1424.

Lilly, D. and Kennedy, P. (1973). Observations of a stationary mountain wave and its associated momentum flux and energy dissipation. *J. Atmos. Sci.*, 30:1135–1152.

Rontu, L. (2007). Studies on orographic effects in a numerical weather prediction model. *Finish Meteorological Institute report*.

Shepherd, T. (2000). The middle atmospheres. *J. Atmos. Solar-Terr. Phys.*, 62:1587–1601.

Ullrich, P. A., Lauritzen, P. H., and Jablonowski, C. (2009). Geometrically exact conservative remapping (GECoRe): Regular latitude-longitude and cubed-sphere grids. *Mon. Wea. Rev.*, 137(6):1721–1741.