Gravity Wave Parameterizations in the NCAR CESM

Julio Bacmeister, Peter Lauritzen, Patrick Callaghan, Jerry Olson **NCAR**

NCAR
NATIONAL CENTER FOR ATMOSPHERIC RESEARCH

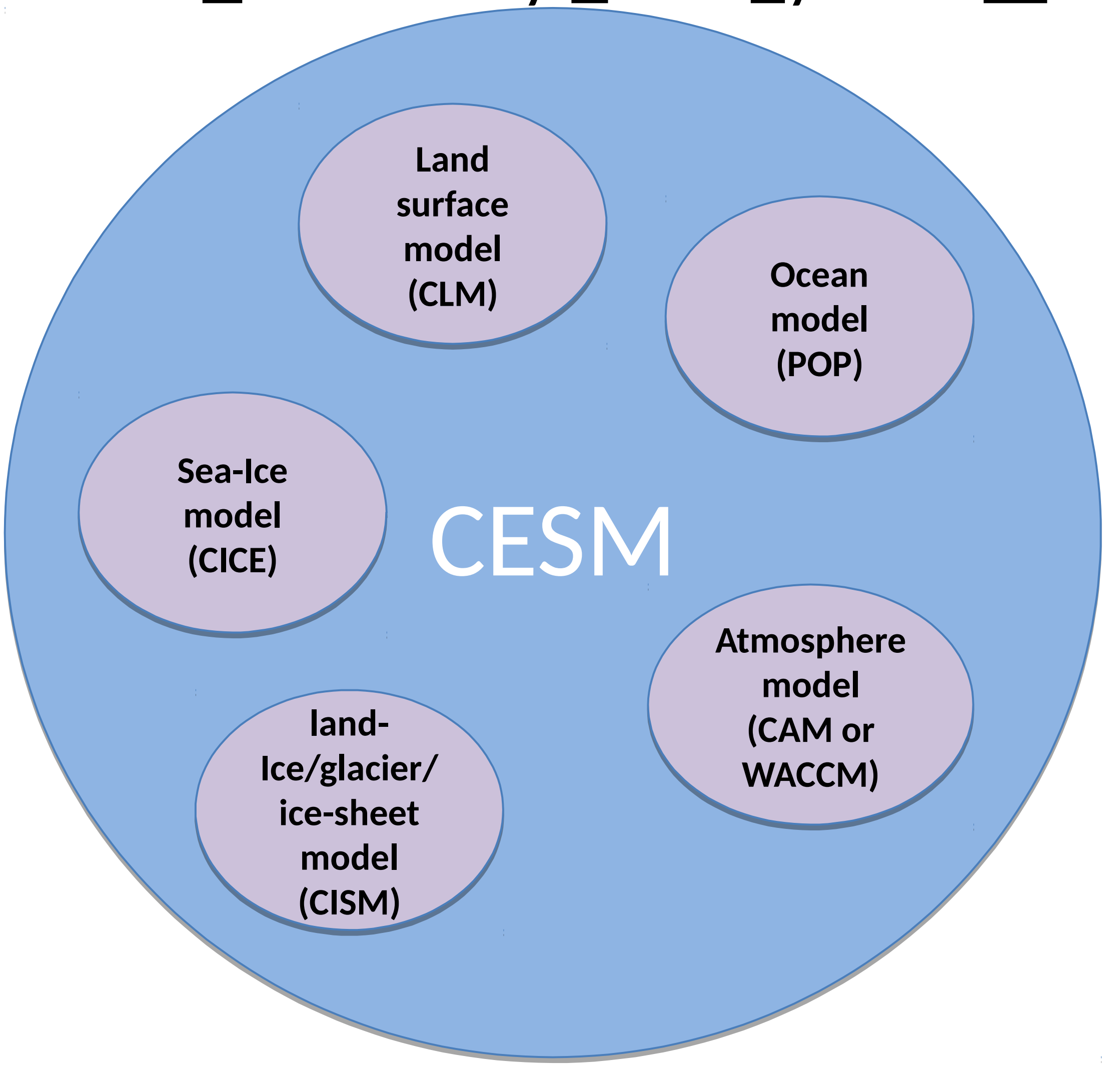
DEEPWAVE Workshop, New Haven CT, 8 August 2017

Overview

- Background - WACCM/CAM/CESM
- New Developments for GWP
  - Ancillary topography files
  - Anisotropic/blocking scheme
- Results
  - AMIP runs
  - DART assimilation runs to assess parameterization
- Future Directions

WACCM, CAM, CESM ..., CCSM, CSM, ... ??

CESM=Community Earth System Model



WACCM, CAM, CESM …, CCSM, CSM, … ??

Atmosphere model (CAM or WACCM)

- CAM=Community Atmosphere Model
- WACCM=Whole Atmosphere Community Climate Model
- CAM: model top at ~2hPa (~45km). Poorly resolved stratosphere. Simplified chemistry.
- WACCM: model top ~110km. Non-LTE, ions, …
- Both CAM and WACCM are run fully-coupled (w/ dynamic ocean) or in stand-alone (w/ prescribed sea-surface temperatures)
- CAM and WACCM are (nearly) the same model below 45km, although WACCM has usually been a version or two behind in the troposphere. *Trying to change this in CESM2.*
- CAM GWP includes only orographic source. WACCM GWP has frontal and convective sources as well.
- Typical horizontal resolution for long integrations: 100km

Model	CAM3 CCSM3	CAM4 CCSM4	CAM5 CESM1.0	CAM5.2 CESM1.1	CAM6 CESM2
Release	**Jun 2004**	**Apr 2010**	**Jun 2010**	**Nov 2012**	**Sometiime 2017**
PBL	Holtslag-Boville (1993)	Bretherton et al (2009)	Bretherton et al (2009)	Bretherton et al (2009)	CLUBB
Orographic form drag			Richter et al. (2010)	Richter et al. (2010)	Beljaars et al.2003
GW drag	McFarlane (1987)	McFarlane (1987)	McFarlane (1987) (non-orographic source updated for WACCM)	McFarlane (1987)	Anisotropic/Low-level nonlinearities
Shallow Convection	Hack (1994)	Hack (1994)	Park et al. (2009)	Park et al. (2009)	CLUBB
Deep Convection	Zhang-McFarlane (1995)	Neale et al. (2008)	Neale et al. (2008)	Neale et al. (2008)	Neale et al. (2008)
Microphysics	Rasch-Kristjansson (1998)	Rasch-Kristjansson (1998)	Morrison-Gettelman (2008)	Morrison-Gettelman (2008)	Morrison-Gettelman v2 (2014)
Macrophysics	Rasch-Kristjansson (1998)	Rasch-Kristjansson (1998)	Park et al. (2011)	Park et al. (2011)	CLUBB
Radiation	Collins et al. (2001)	Collins et al. (2001)	Iacono et al. (2008)	Iacono et al. (2008)	Iacono et al. (2008)
Aerosols	Bulk Aerosol Model	Bulk Aerosol Model BAM	Modal Aerosol Model Ghan et al. (2011)	Modal Aerosol Model Ghan et al. (2011)	Modal Aerosol Model Ghan et al. (2011)
Dynamics	Spectral	Finite Volume	Finite Volume	Spectral element	Finite Volume

= switch/update

Orographic GW drag in CAM

McFarlane, N. A. (1987). The effect of orographically excited gravity wave drag on the general circulation of the lower stratosphere and troposphere. *Journal of the Atmospheric Sciences*, *44*(14), 1775-1800.

Isotropic topography. No low-level blocking. Lindzen-type wave model

Orographic GWP drag in CAM

Never Implemented in CAM: Anisotropy, low-level blocking, e.g.;

Lott, F., and M. J. Miller (1997). A new subgrid-scale orographic drag parametrization: Its formulation and testing.   *Quarterly Journal of the Royal Meteorological Society* 123.537: 101-127.

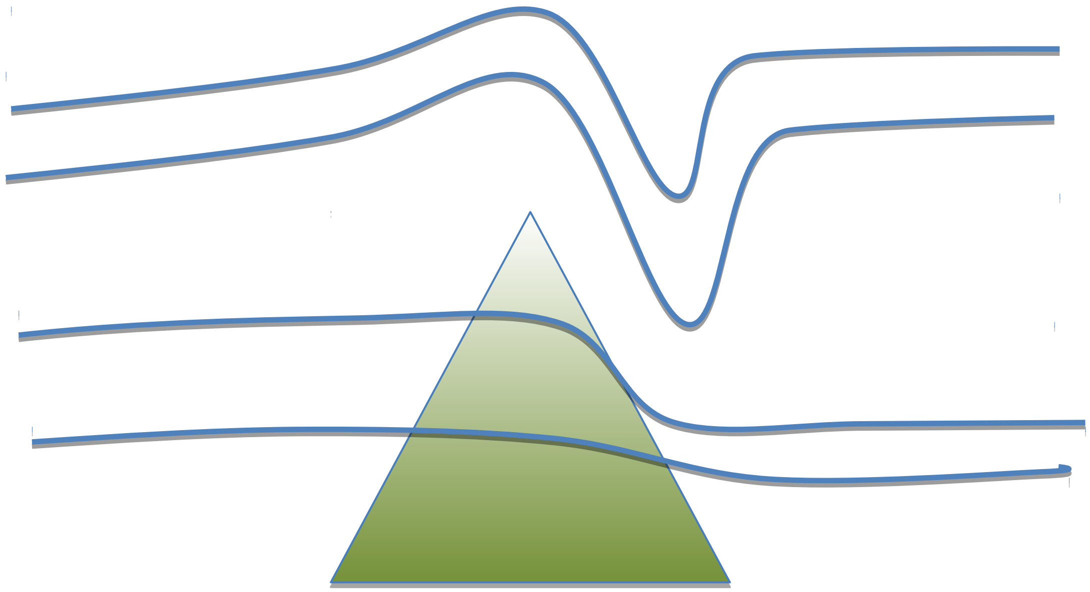
Gregory, D., Shutts, G. J., & Mitchell, J. R. (1998). A new gravity-wave-drag scheme incorporating anisotropic orography and low-level wave breaking: Impact upon the climate of the UK Meteorological Office Unified Model. *Quarterly Journal of the Royal Meteorological Society*, *124*(546), 463-493.

Scinocca, J. F., & McFarlane, N. A. (2000). The parametrization of drag induced by stratified flow over anisotropic orography. *Quarterly Journal of the Royal Meteorological Society*, *126*(568), 2353-2393.

Alpert, J. C. (2004) Sub-grid scale mountain blocking at NCEP. *Proceedings of 20th Conference on WAF, 16th conference on NWP*.

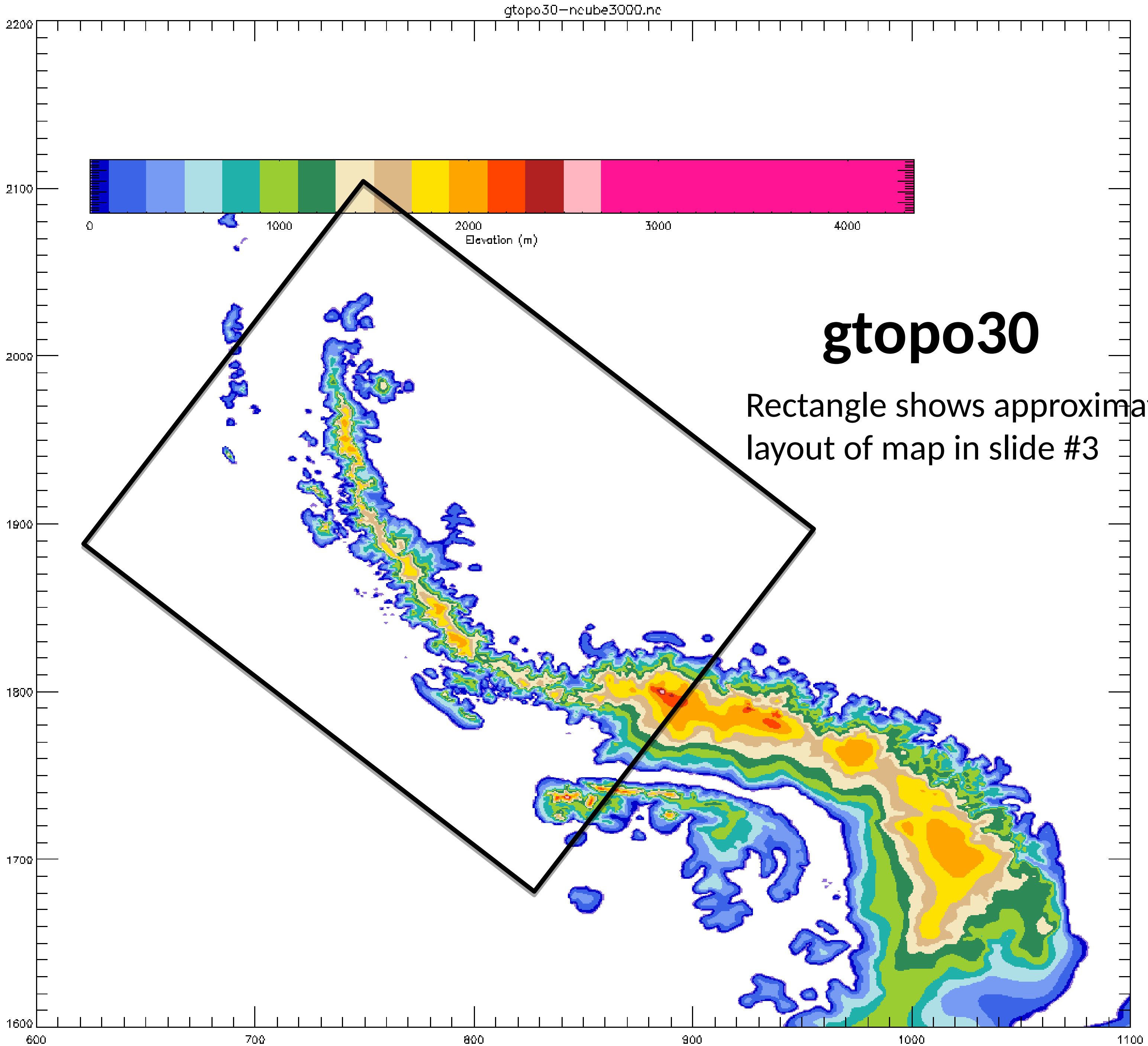
Blocking, low-level turning

Parameterization allows flow around obstacles – *form drag* - as well as “downslope wind” high-drag dynamics (*following Scinocca&McFarlane 2000)*



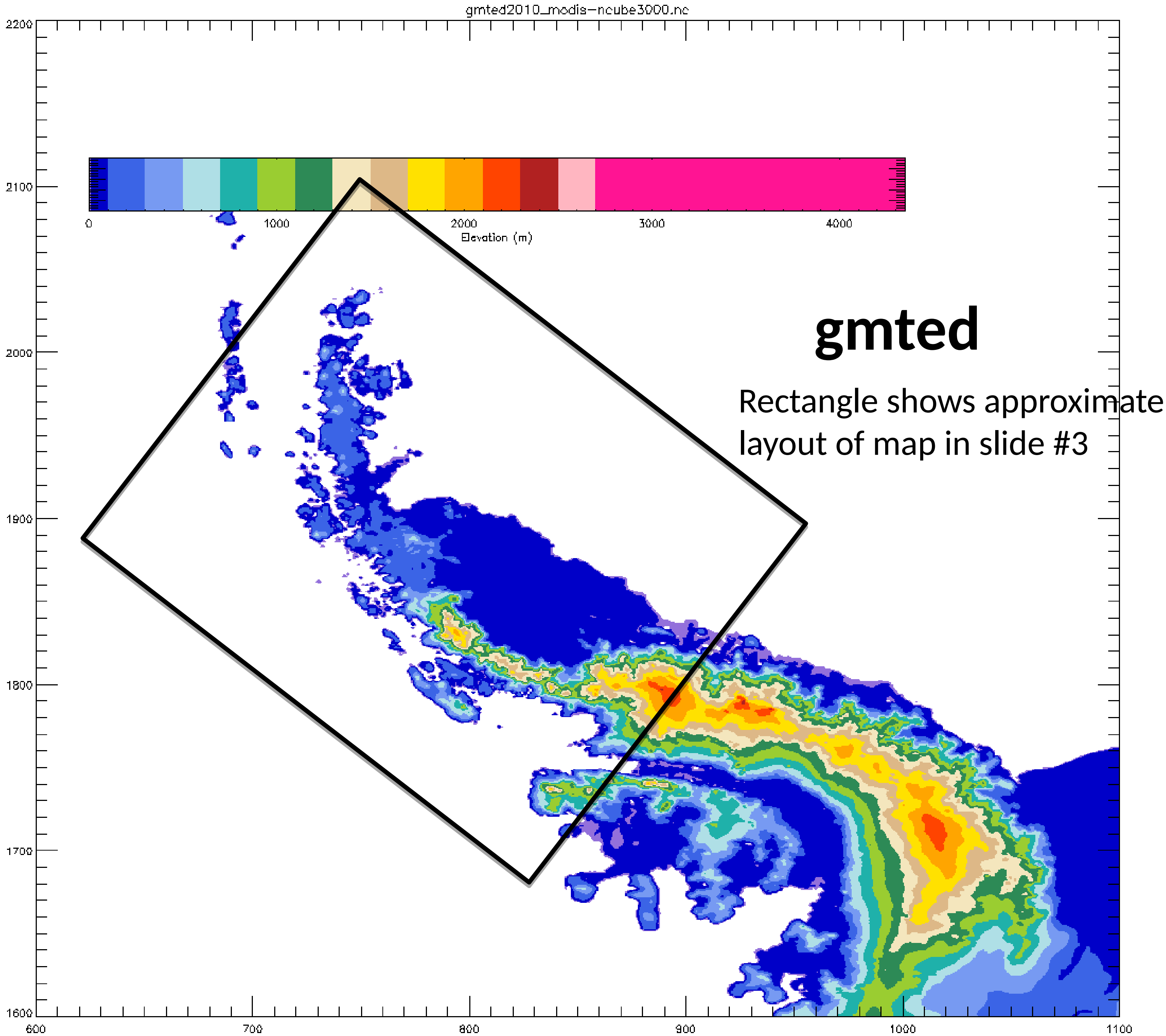
Generation of ancillary topography files

- No traceable process for generating topography forcing data existed for CESM1 or earlier versions.
  - Derivation of subgrid variables and smoothing of mean elevations left up to dycore developers. ***Note: all dycores employ additional smoothing beyond binning to grid.***
- New procedure starts from 1km GMTED2010 data (or GTOPO30) mapped to 3km cubed sphere grid. Further processing follows from 3km cubed sphere topo (*Lauritzen et al. GMD 2015*)



gtopo30

Rectangle shows approximate layout of map in slide #3

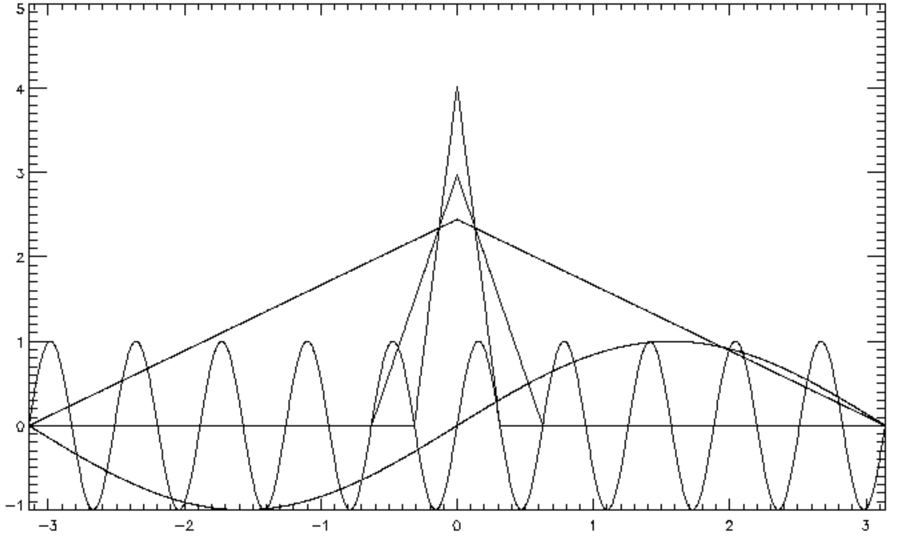


gmted2010_modis-ncube3000.nc
Elevation (m)
0
1000
2000
3000
4000
2200
2100
2000
1900
1800
1700
1600
600
700
800
900
1000
1100
gmted
Rectangle shows approximate layout of map in slide #3

Generation of ancillary topography files

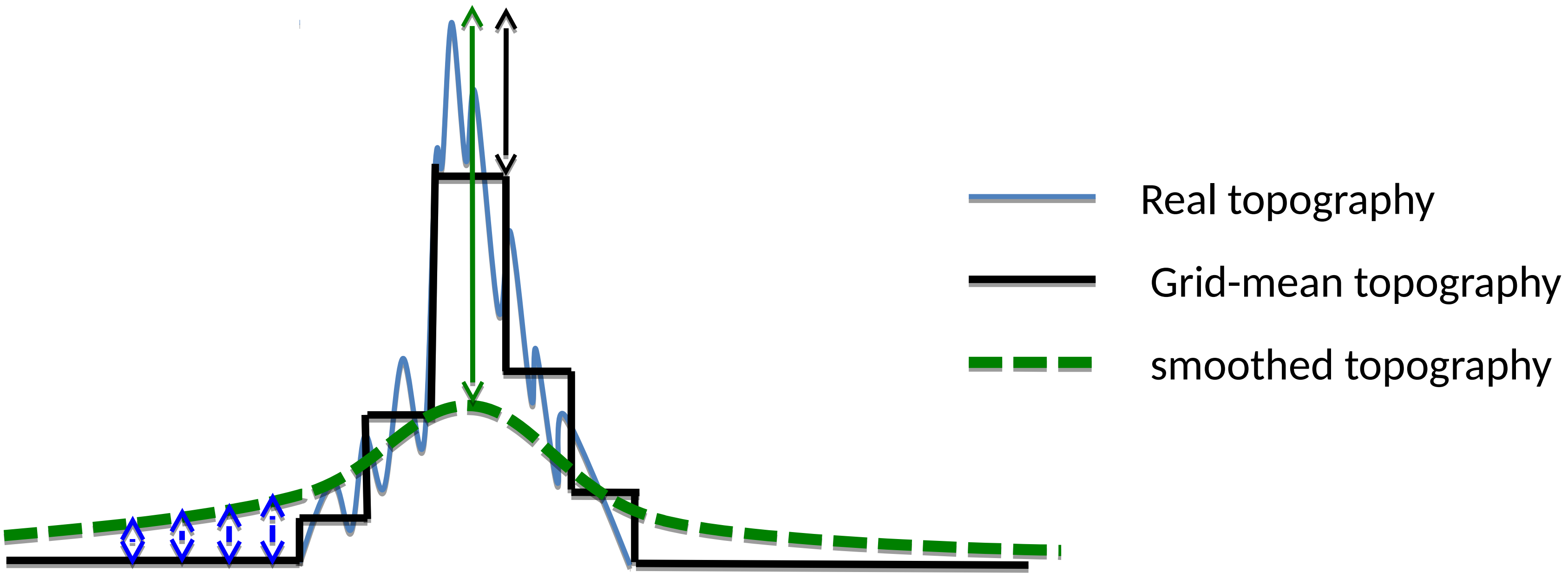
- What are orographic GWP supposed to represent?
- What is most realistic way to force orographic GWP?

Subgrid variance may not be a good way to diagnose forcing for orographic gravity waves



Cross-sections with approximately equal variances

Sub-grid vs. unresolved

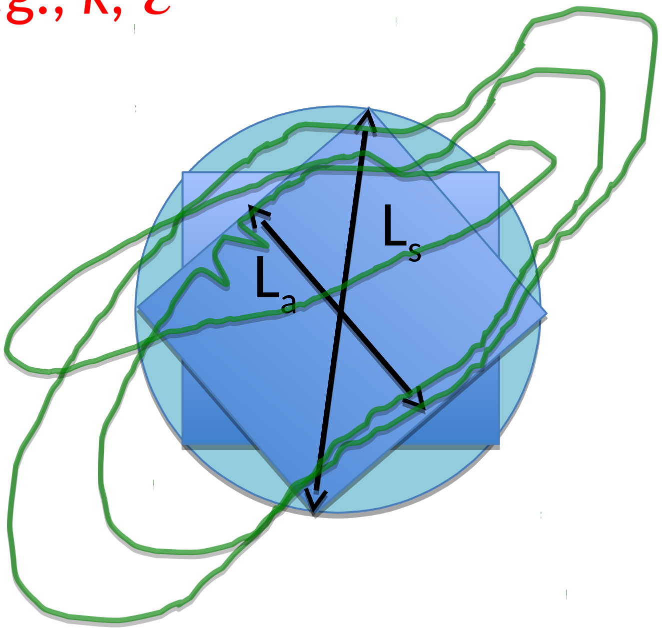


Given that most models smooth topography. What should be parameterized – true sub-grid topography or deviation from smoothed topography?

Feature-based ridge identification

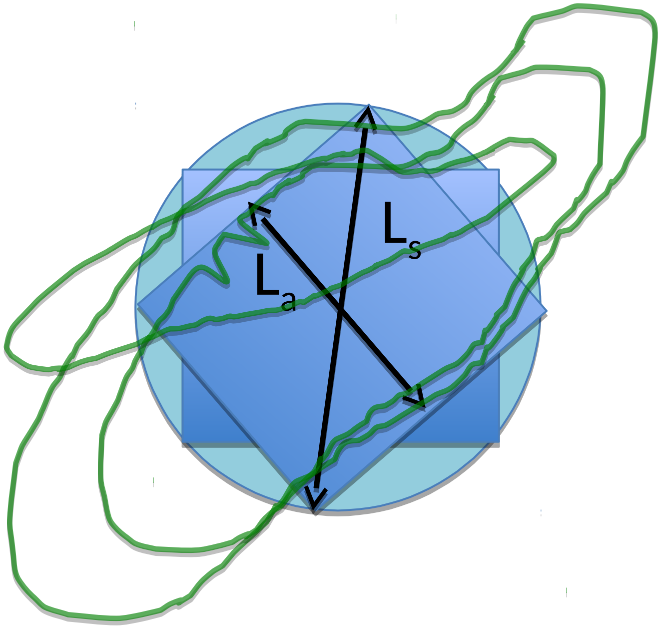
- Smooth topography (scale ~ L_s)
- Calculate variances of mean cross-sectional profiles at 16 different orientations on $L_a x L_a$ domains on dense grid
- Maximum 1D vs 2D variance determines "ridge" angle

Ultimate goal is to improve on globally specified parameters for orographic waves, e.g., *k*, ε

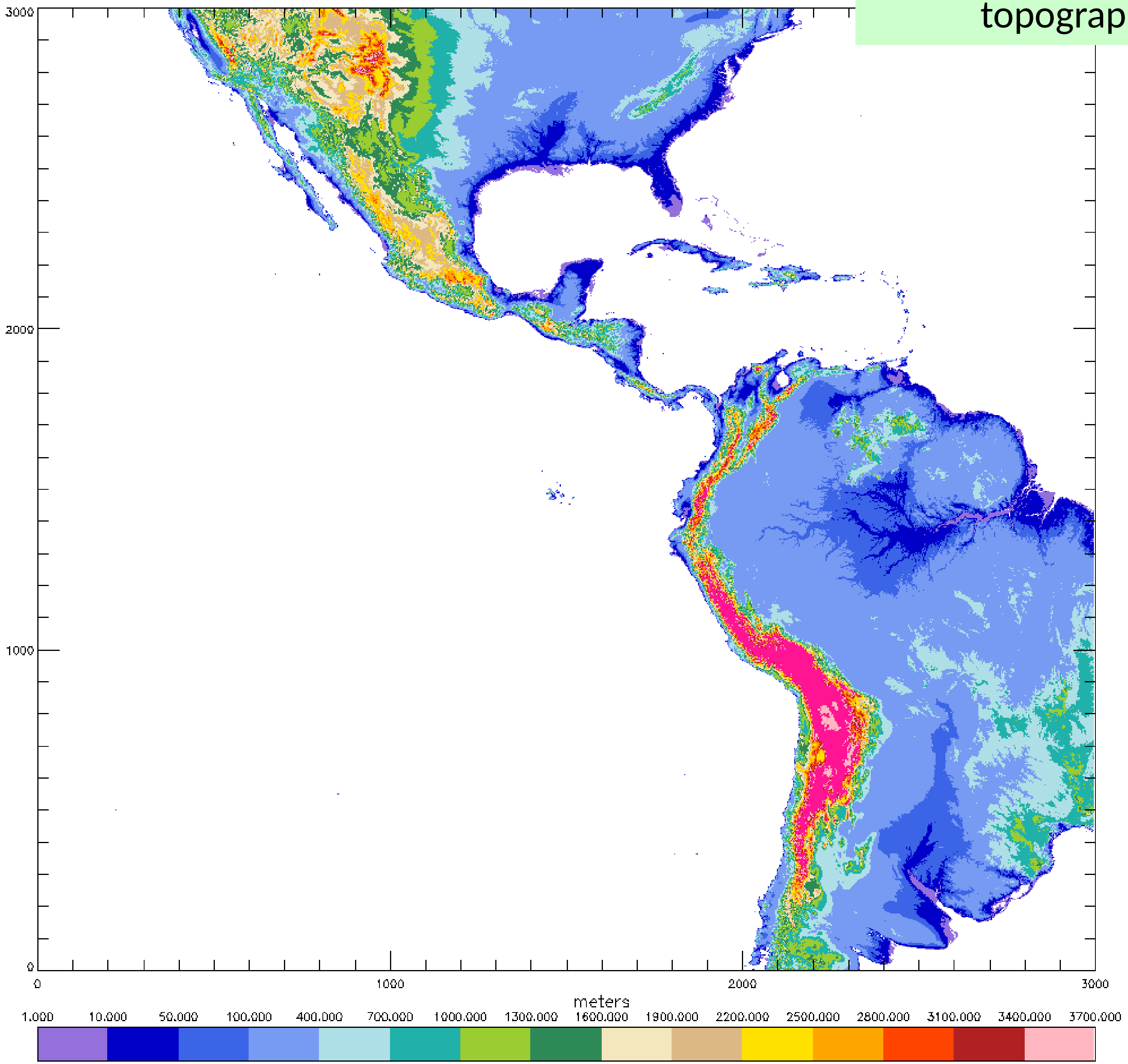


Feature-based ridge identification

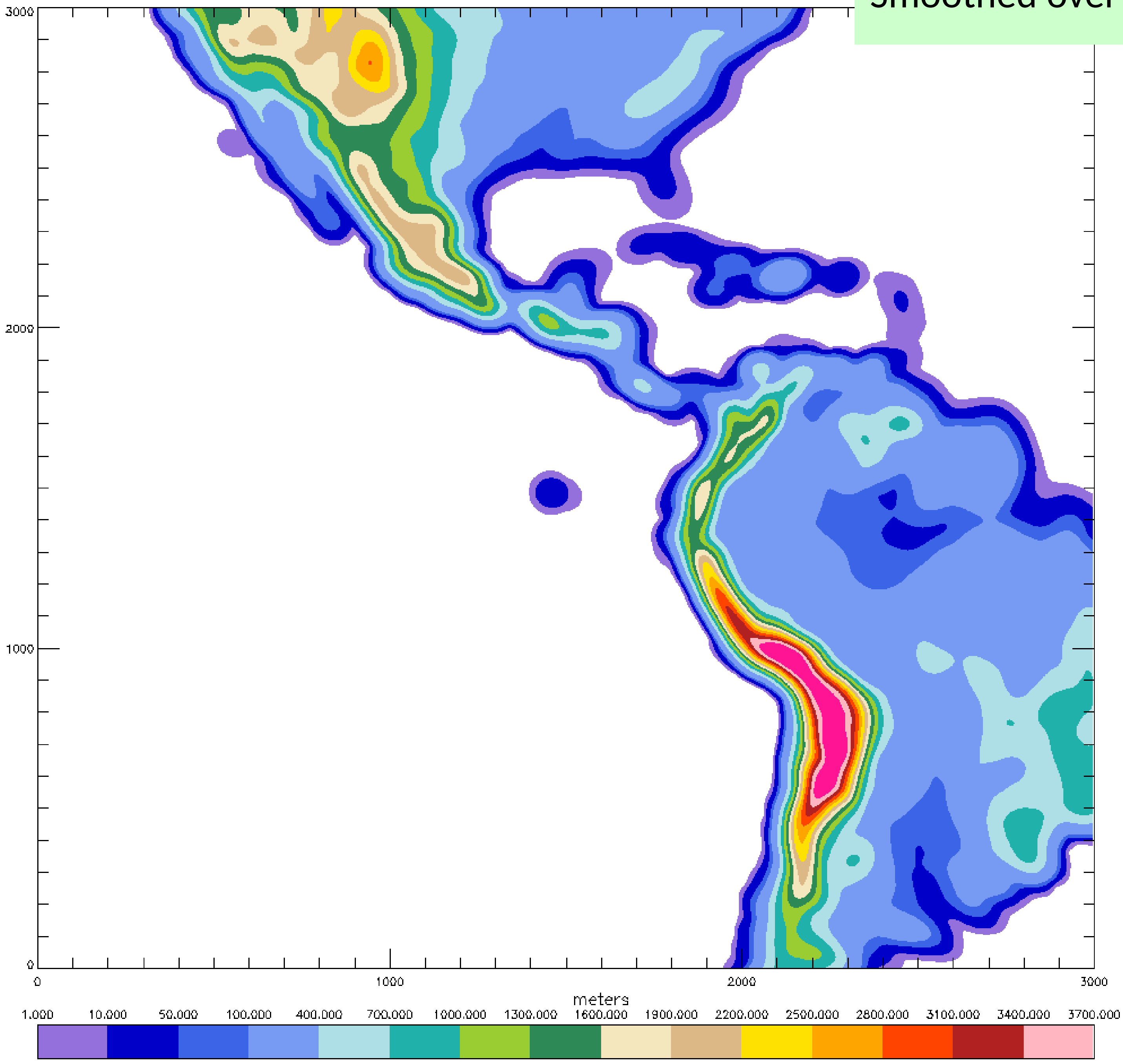
- Outputs
  - Orientation
  - Ridge height from max-min of profile (different from std. dev. of topo)
  - Estimate of ridge width and length
  - Geographically-based estimate of "effgw_oro"
  - "quality": ratio of 1D/2D variance



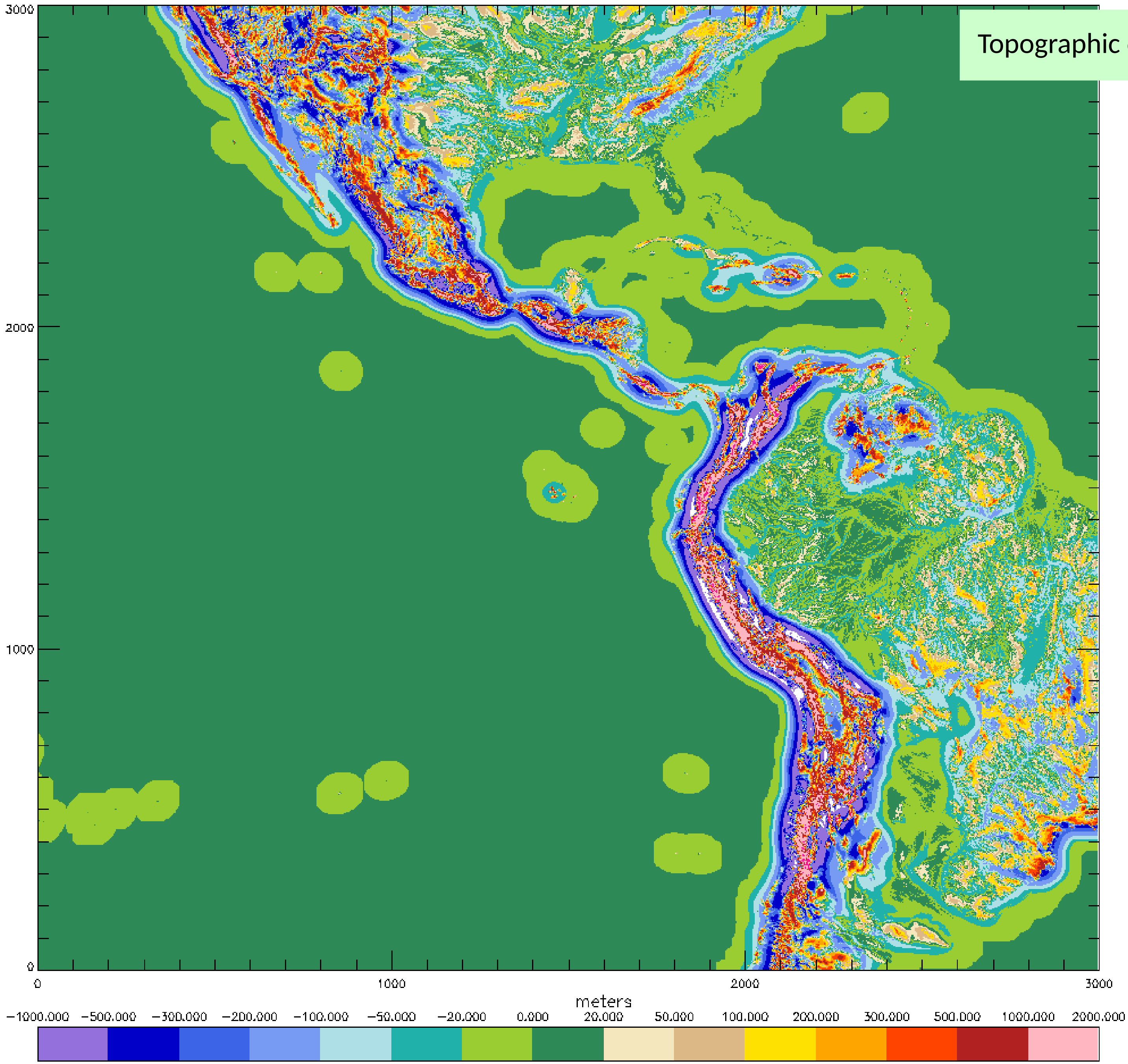
Raw 3km cubed sphere topography



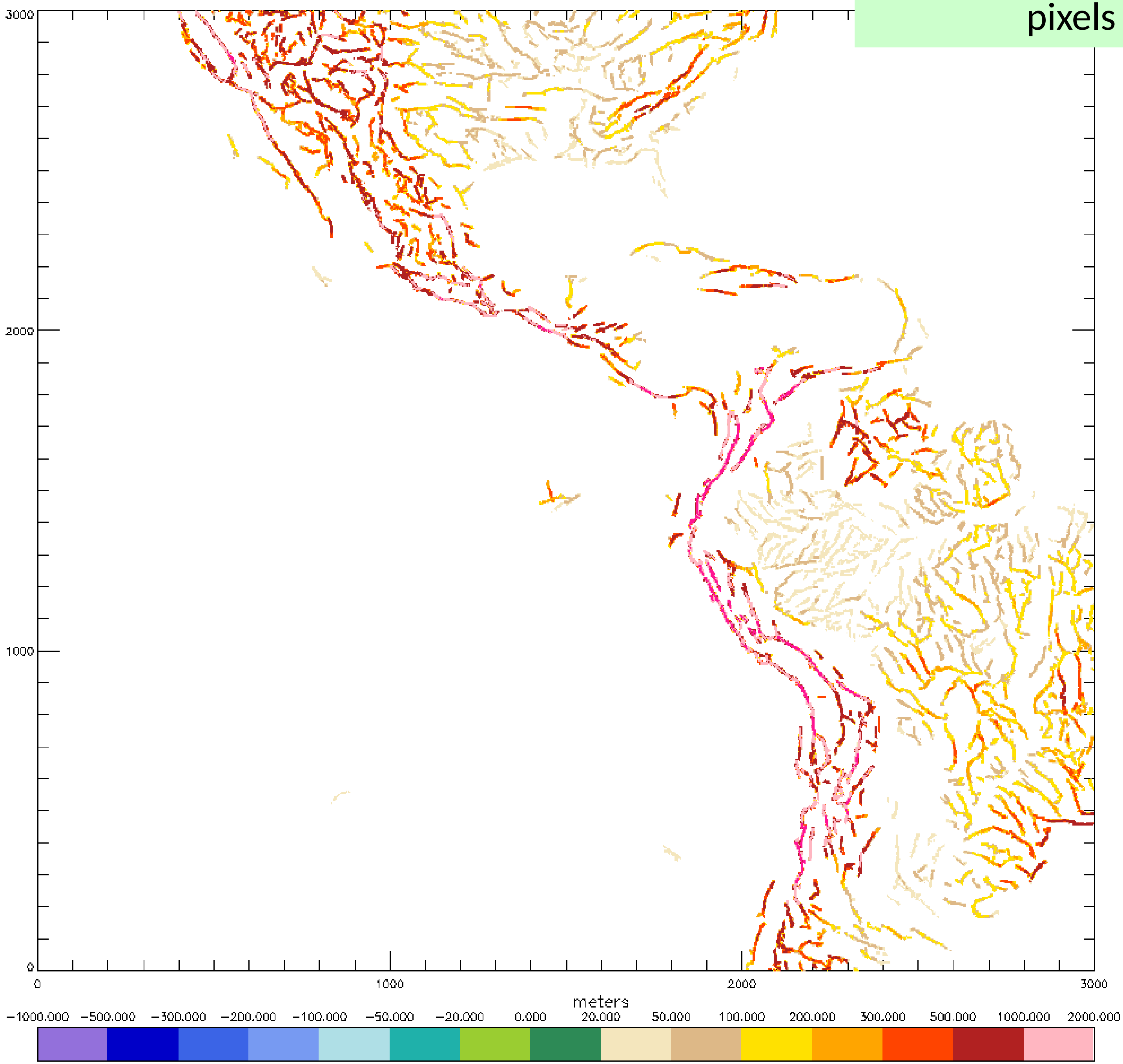
Smoothed over *r*<180km



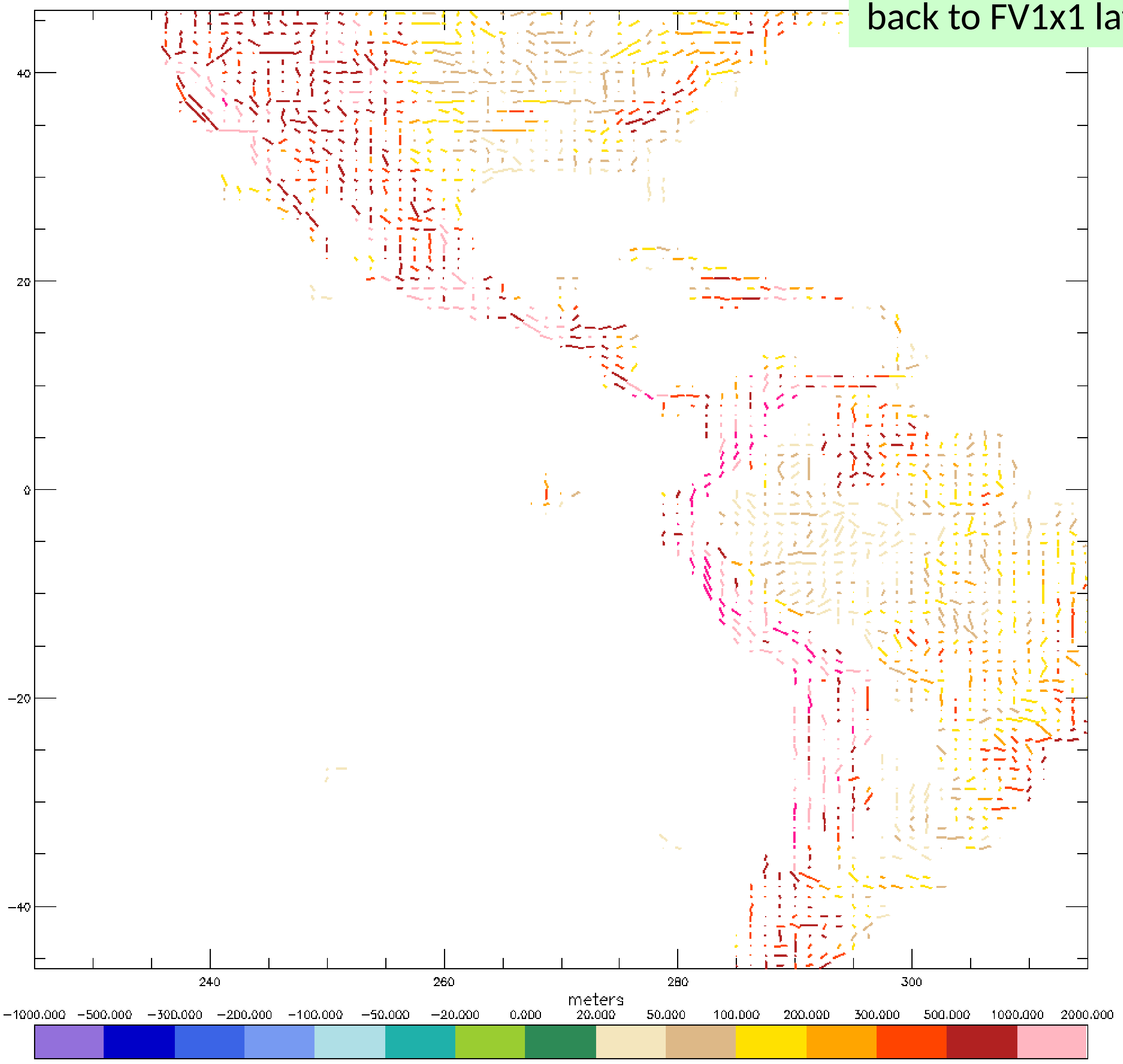
Topographic deviations

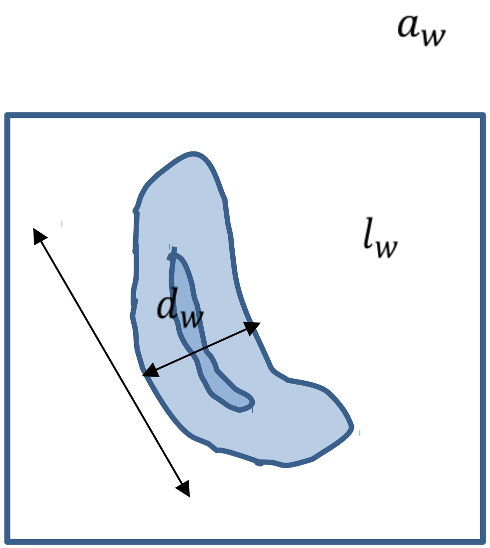


Ridge "skeleton" on 3km pixels



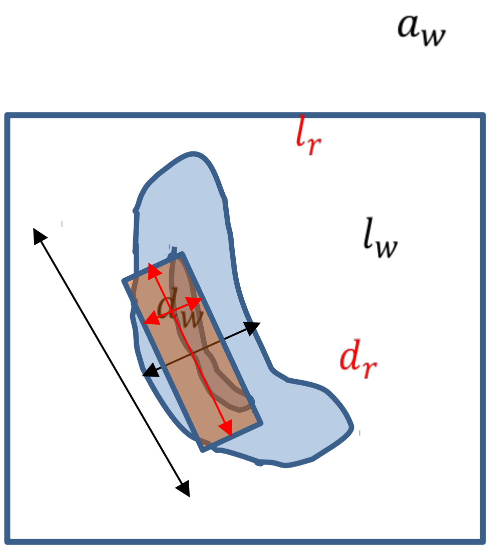
Ridge elements mapped back to FV1x1 latlon grid





$$\rho\overline{u'w'} = \frac{1}{A}\iint \rho u'w'\,dx\,dy \sim \frac{1}{A} a_w \rho c_1 N\delta\; c_2 U \frac{\delta}{l_w}$$

2D, WKB, steady-state, hydrostatic wave model

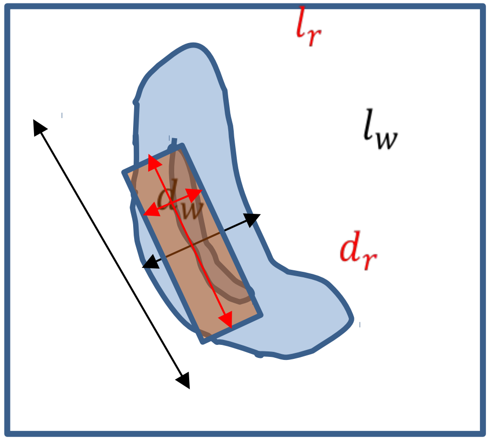


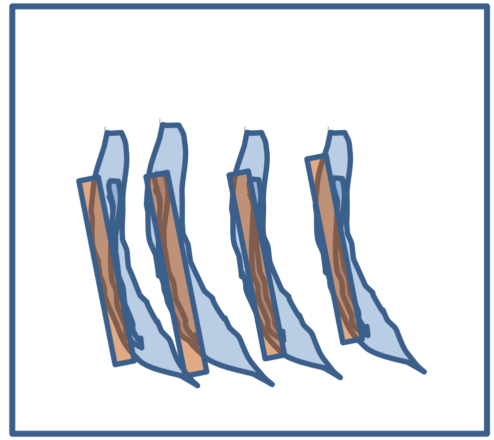
$$\rho\overline{u'w'} = \frac{1}{A}\iint \rho u'w' dx\, dy \sim \frac{1}{A} a_w \rho c_1$$

$$a_w \sim c_3 d_w l_w, \quad l_w \sim c_4 l_r, \quad d_w \sim c_5 d_r$$

$$\delta \approx \mathrm{MIN}(h_r, Fr_c \frac{U}{N})$$

a_w





$$\rho\overline{u'w'} \sim \frac{1}{A} a_w \rho c_1 N\delta \; c_2 U \frac{\delta}{l_w} \sim \frac{1}{A} c_1 c_2 c_3 c_5 d_r \rho N U \delta^2$$

$$a_w \sim c_3 d_w l_w, \qquad l_w \sim c_4 l_r, \qquad d_w \sim c_5 d_r$$

Our first try assumes:

$$\delta \simeq \mathrm{MIN}\left(h_r, Fr\frac{U}{N}\right)$$

$$\rho\overline{u'w'} \sim \frac{d_r}{A} \rho N U \delta^2$$

Original scheme:

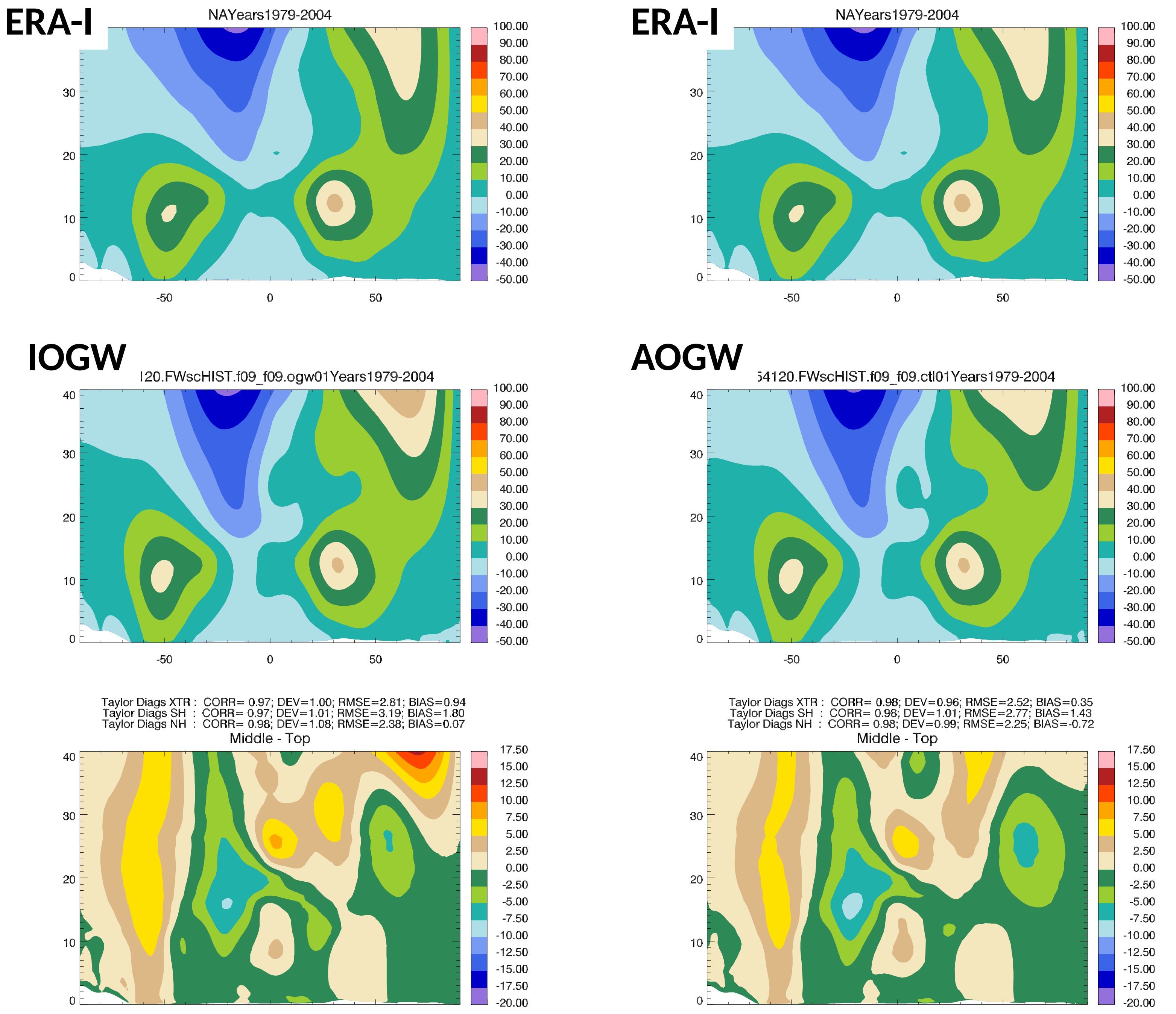
$\sim \varepsilon k_{oro} \rho N U \delta^2$
$\varepsilon = 0.125$
$k = 2\pi/100km$

AMIP runs 1/1979-2/2004

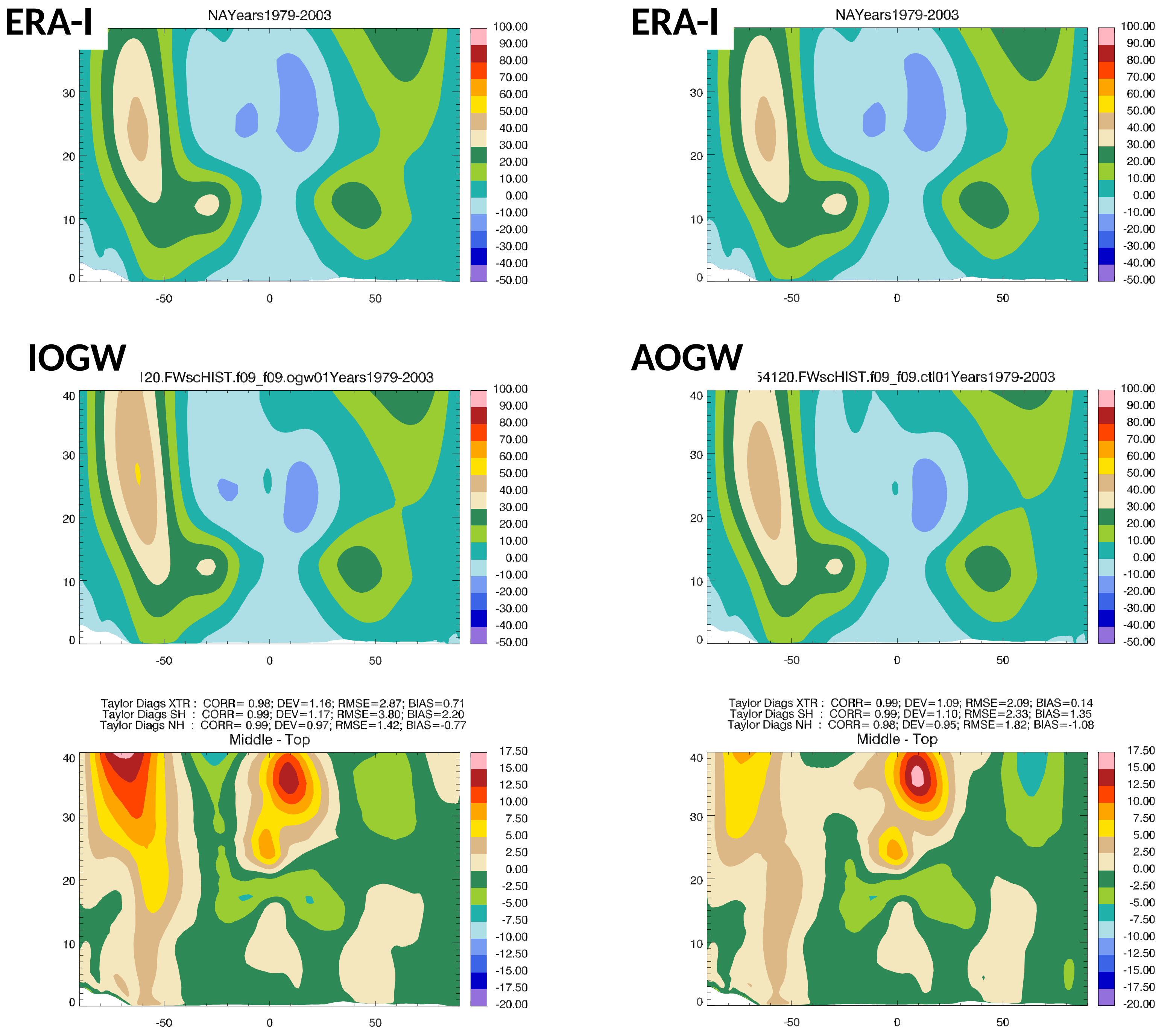
➔***2 configurations of WACCM***

IOGW: Original McFarlane (1987) isotropic gravity wave scheme

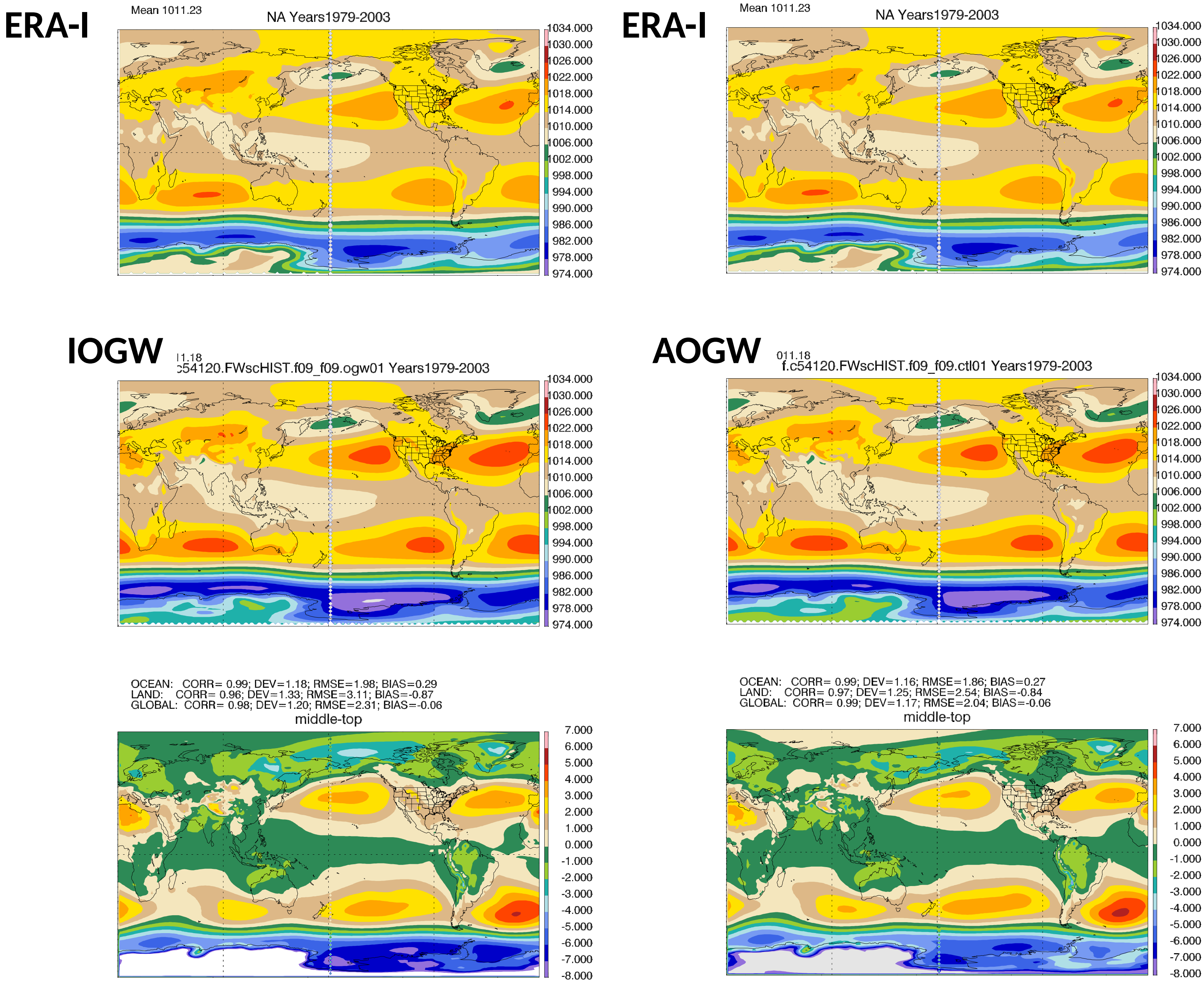
AOGW: New anisotropic scheme



Zonal-mean zonal wind (DJF)



Zonal-mean zonal wind (SON)



ANN PSL

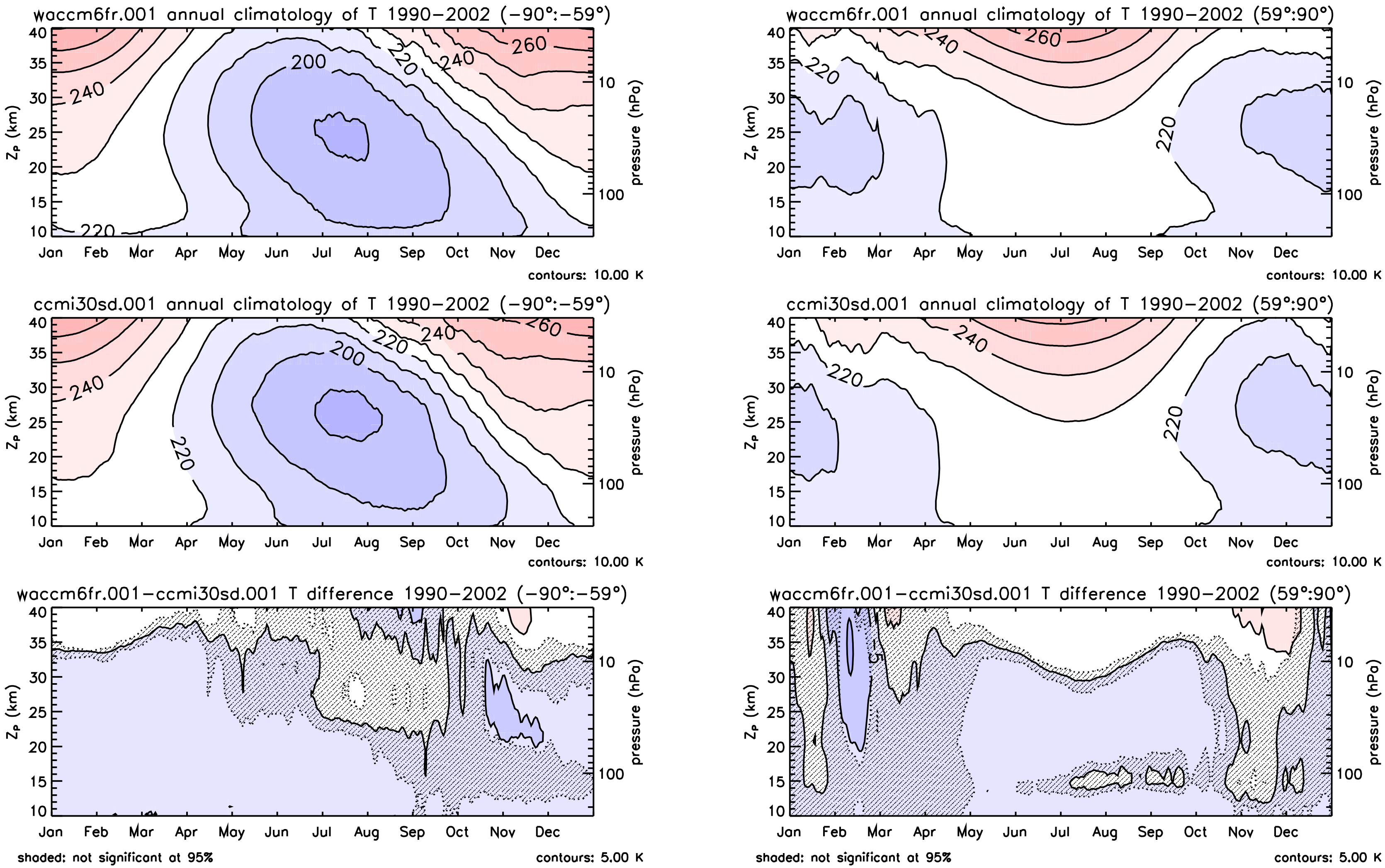
Sea-Level pressure (ANN)

ANN PSL

polar cap T: AOGW vs. MERRA

(from Rolando Garcia)

SH NH

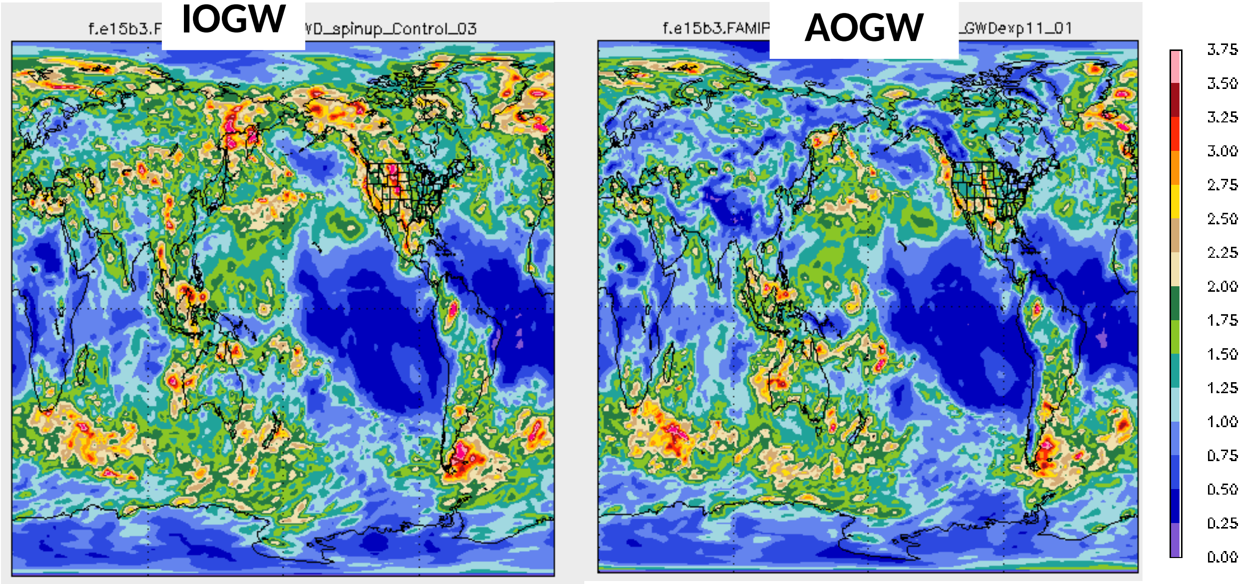


Data Assimilation tests

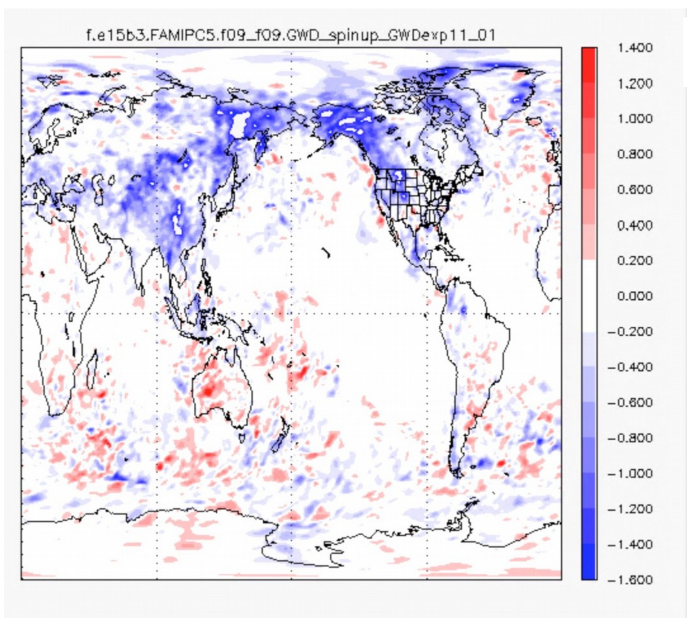
- NCAR’s data assimilation research testbed (DART; Anderson et al .)
- Ensemble Kalman filter
- Radiosondes, cloud track winds, GPS
  – No radiance assimilation
- Look at innovations to assess model performance w/ and w/out new schemes
- Period: Jan 15-Feb 15 2010

DAS increments over 15 Jan-15 Feb 2010

U(100m) (second level)



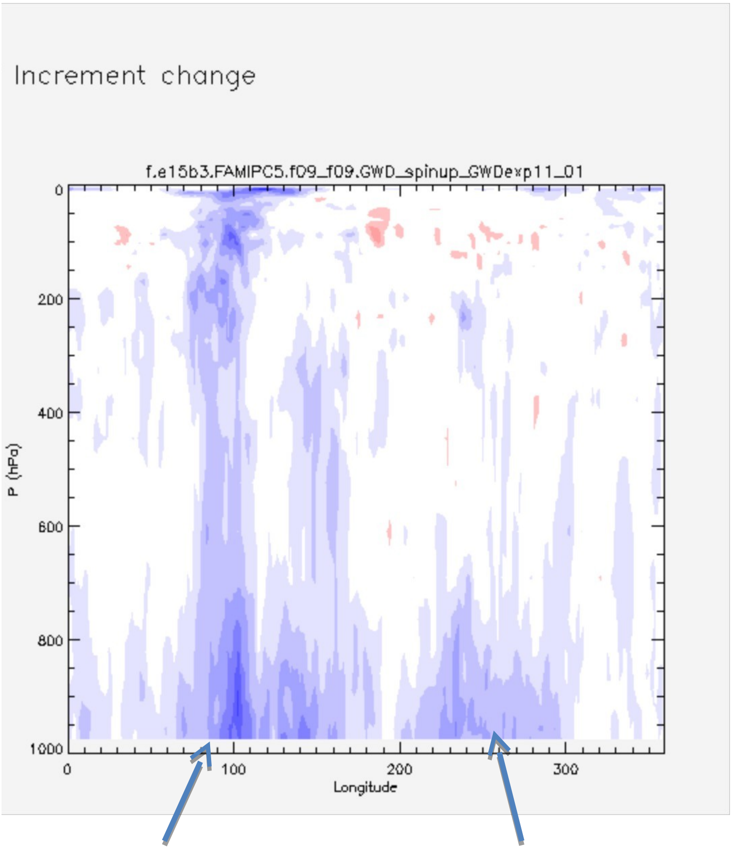
Δ



IOGW better

AOGW better

NH average Δ DAS increments in U over 15 Jan-15 Feb

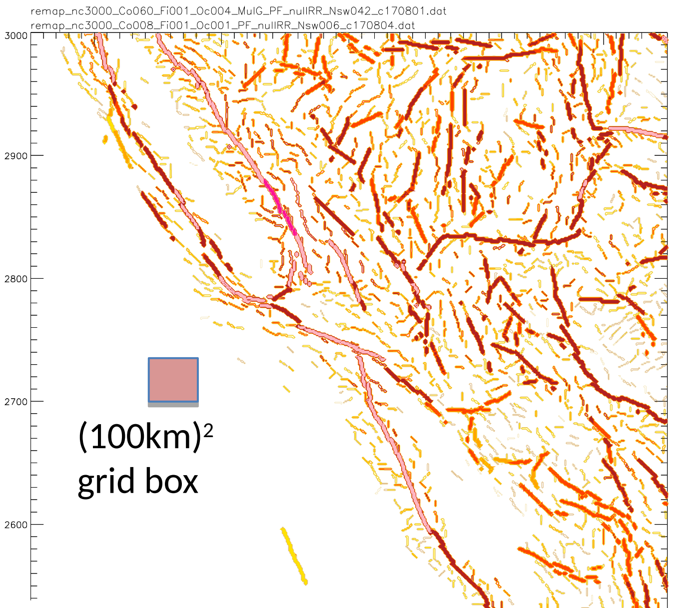


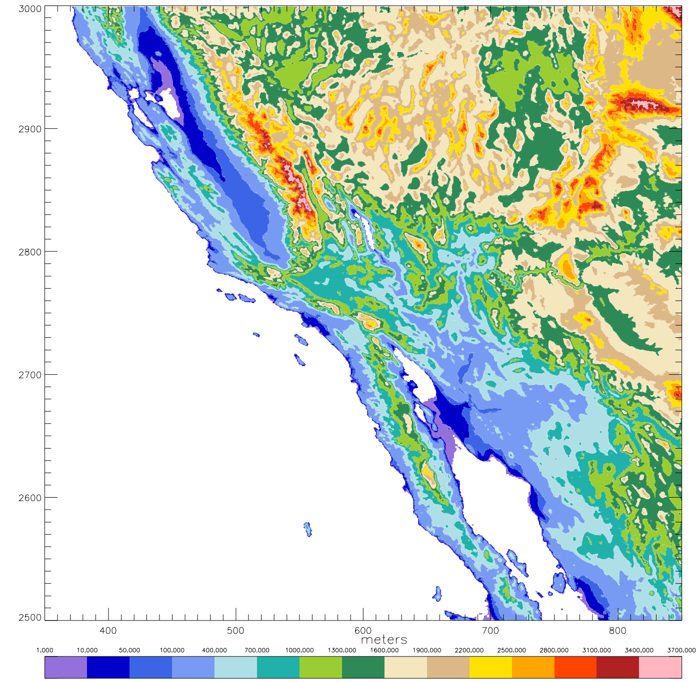
Himalayas

Rockies

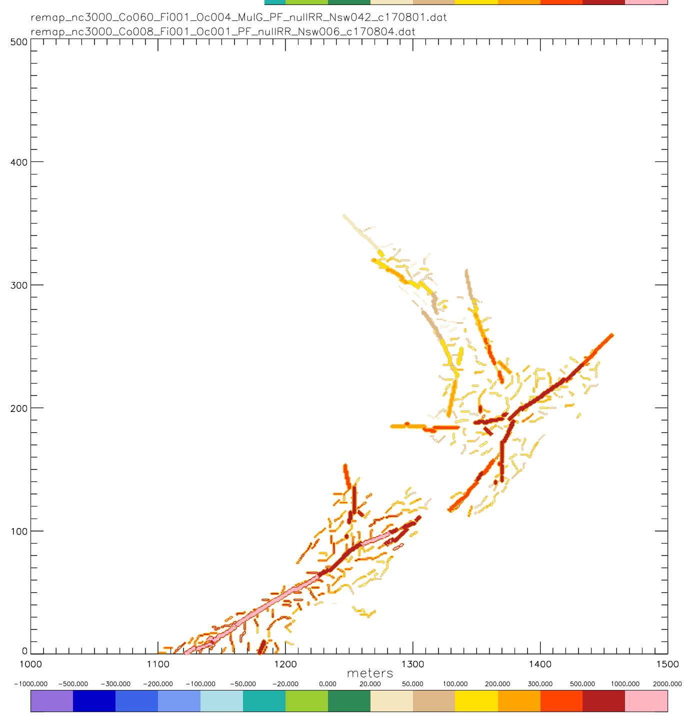
Future directions

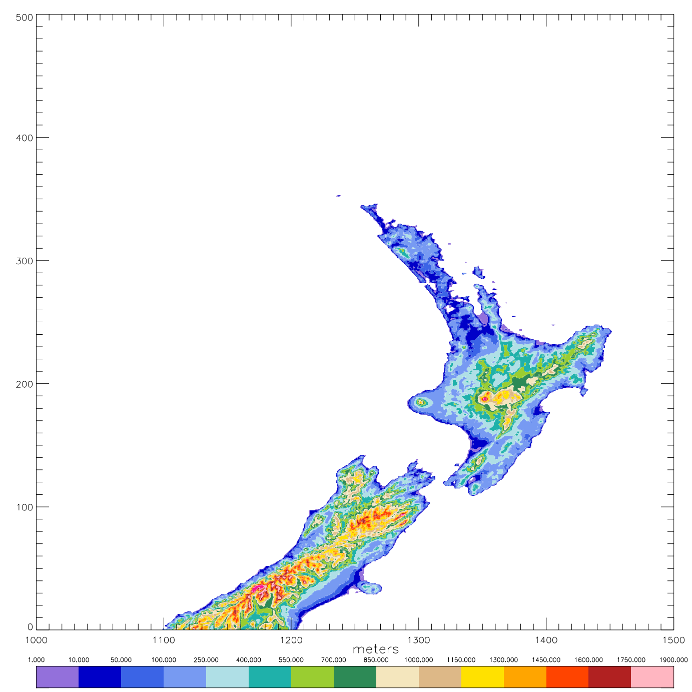
- Multiple bands of orography





Thick lines: *r*=180km smoothing
Thin lines: *r*=24km smoothing

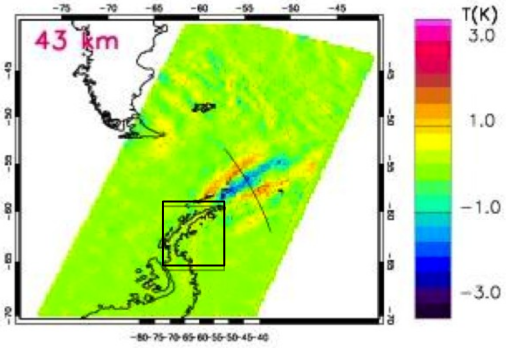




Future directions

Trapping effects not actually included in current parameterizations.

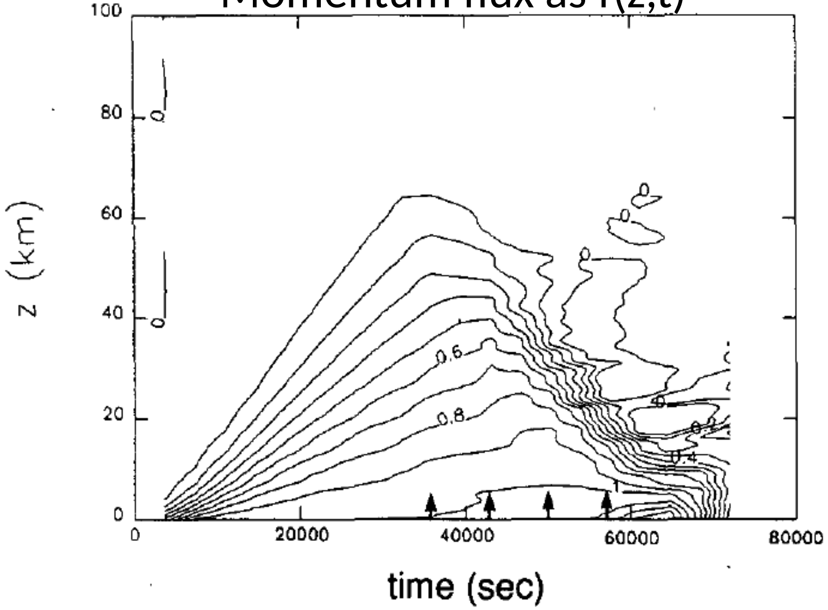
Horizontal propagation of waves across grid boxes (time-dependence also? Ray-based? Super-param.?)

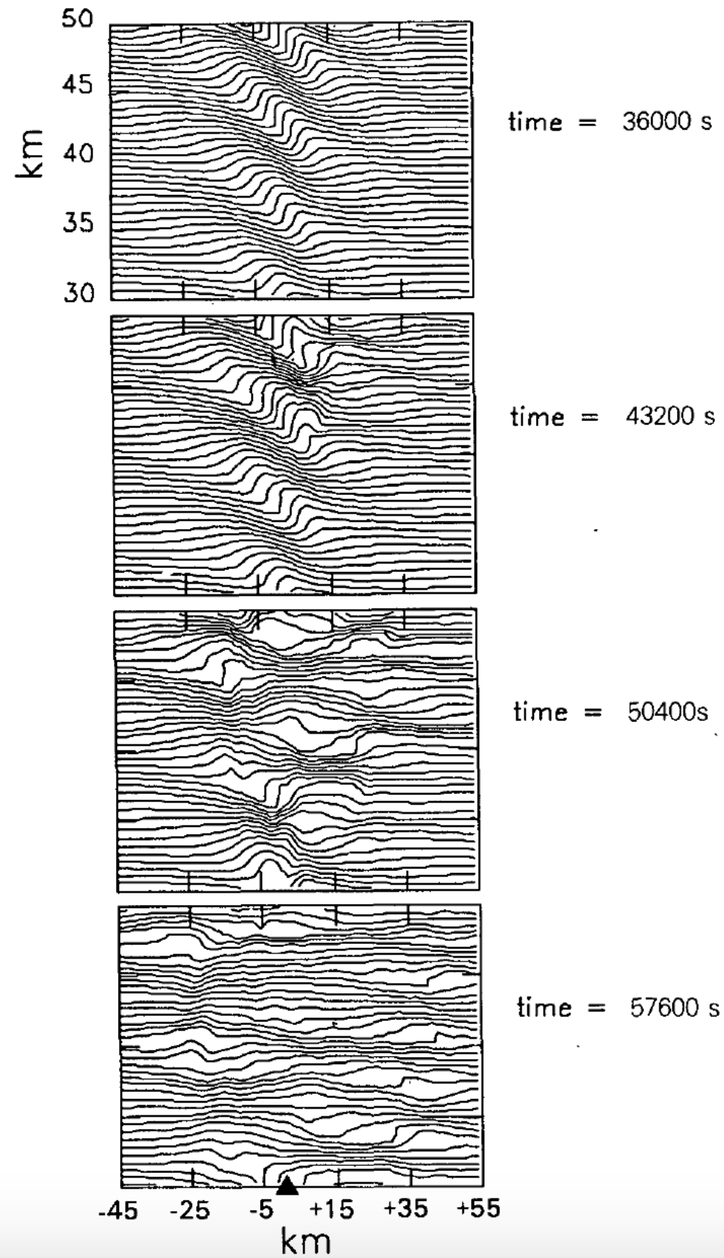


Future directions

Saturation hypothesis – reality?

Momentum flux as f(z,t)





Bacmeister&Schoeberl 1989

Future directions

Wave cloud radiative effects and chemical effects

Nacreous ice-clouds in stratosphere

Final Question

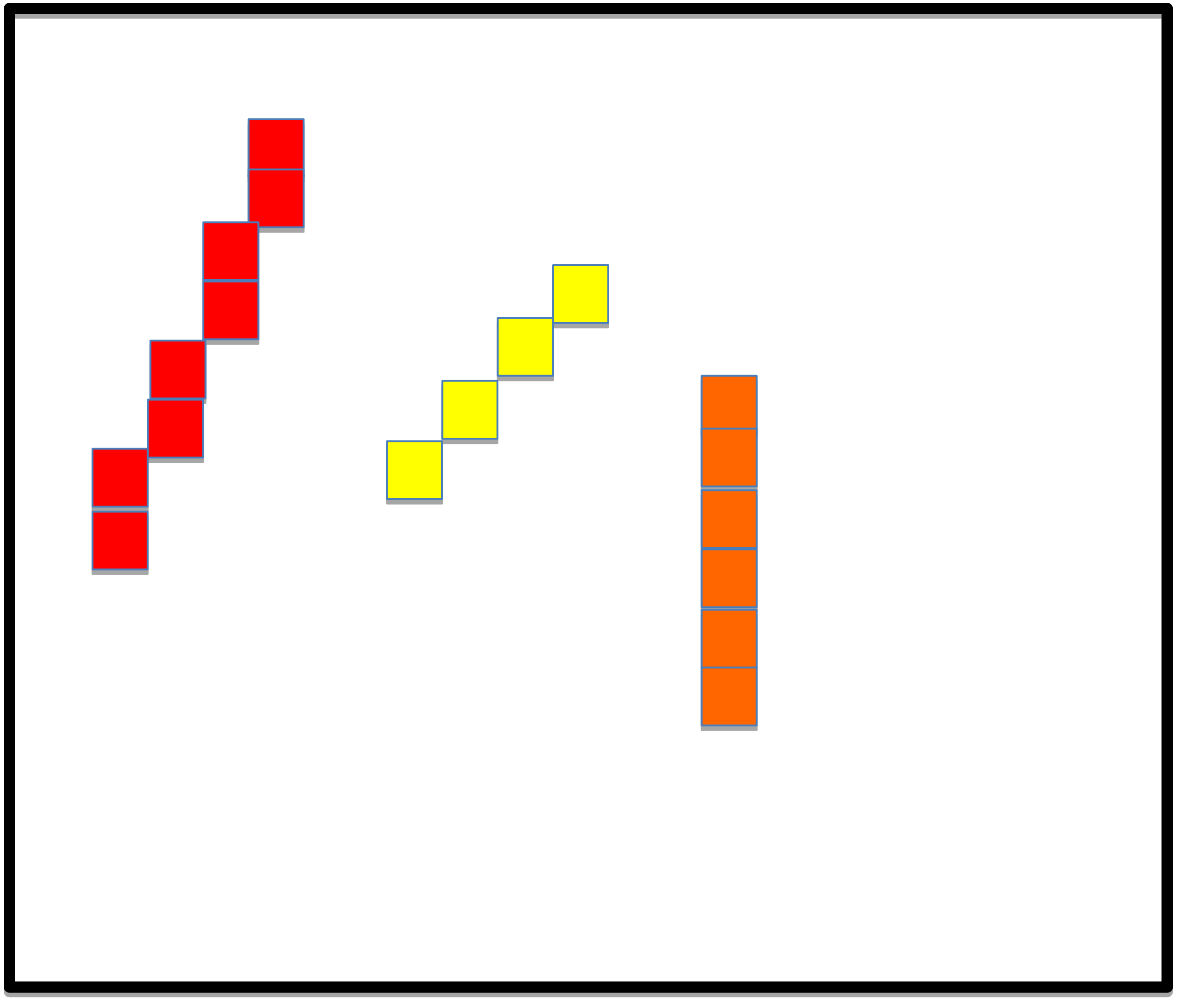
At which resolution can we live without parameterizations of orographic drag?

- *Based on CAM, GEOS5* ***not*** 25km. ... 5km?

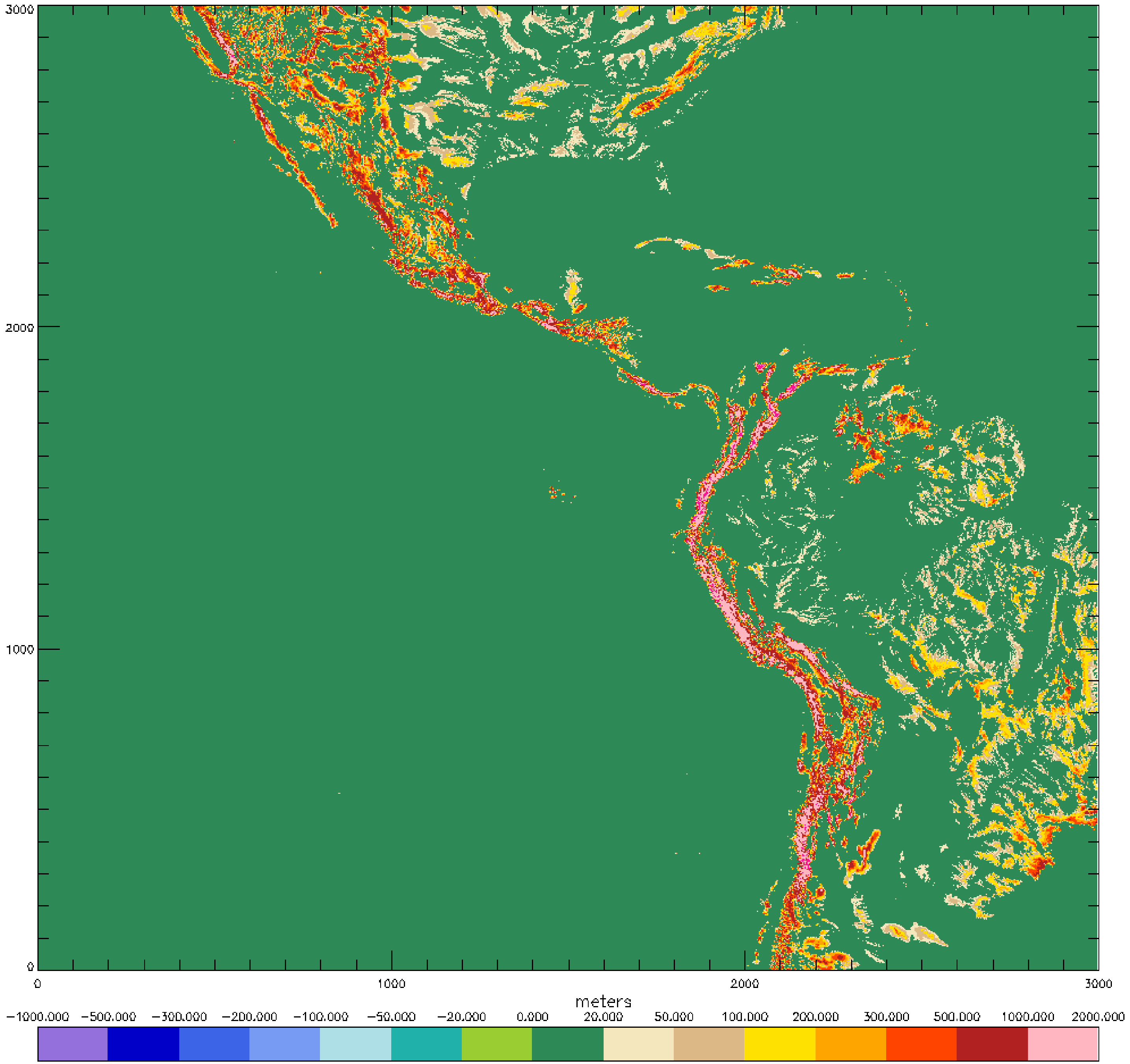
How do we answer the question: Climate simulations? Forecasts?

Thank You

3km pixels are along ridge lines. Each contains estimates of height, width, orientation



180km



3000
2000
1000
0
0
1000
2000
3000
meters
−1000.000 −500.000 −300.000 −200.000 −100.000 −50.000 −20.000 0.000 20.000 50.000 100.000 200.000 300.000 500.000 1000.000 2000.000

PBL Form drag – "Turbulent Mountain Stress (TMS)"

Enhanced roughness length z_0 over rough/hilly terrain, e.g., "turbulent mountain stress" (TMS) scheme currently in CESM (Richter et al. 2010)

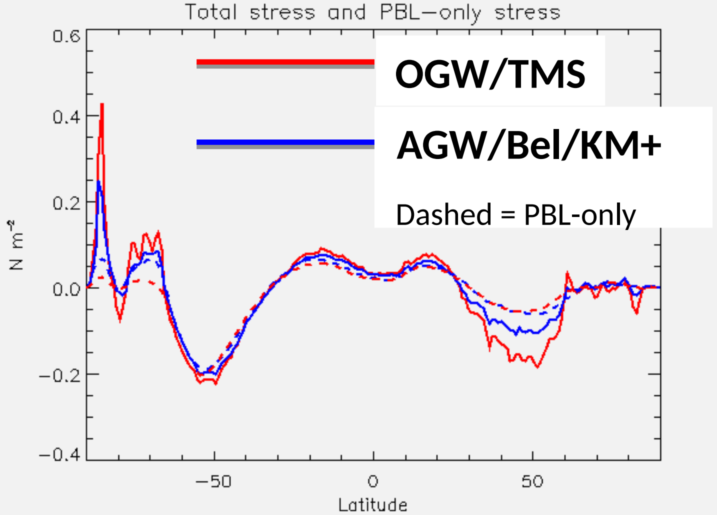
$$\mathbf{F}_x = C_D \,|\,\mathbf{U}\,|\, U(z)$$

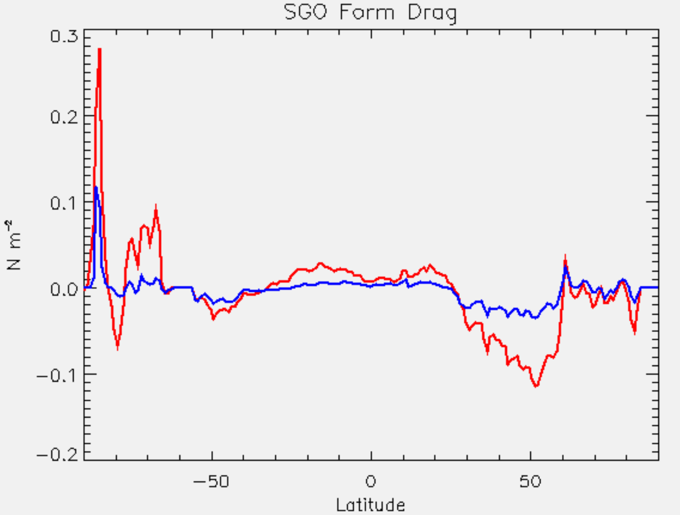
$$C_D = \kappa \left(\ln \left(\frac{z}{z_0} \right) \right)^{-2}$$

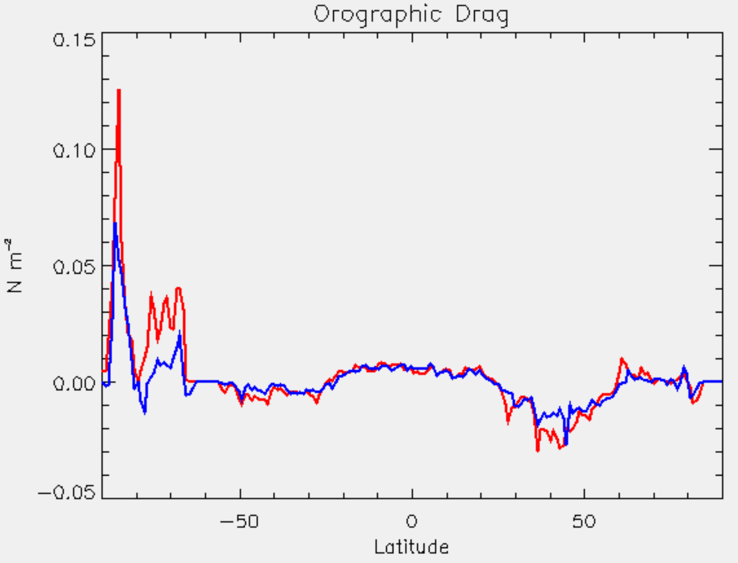
z_0 is roughness length

z_0 is assumed proportional to $\sqrt{\langle h'^2_\delta \rangle}$ where h'_δ is topographic variability for scales λ<3km-5km

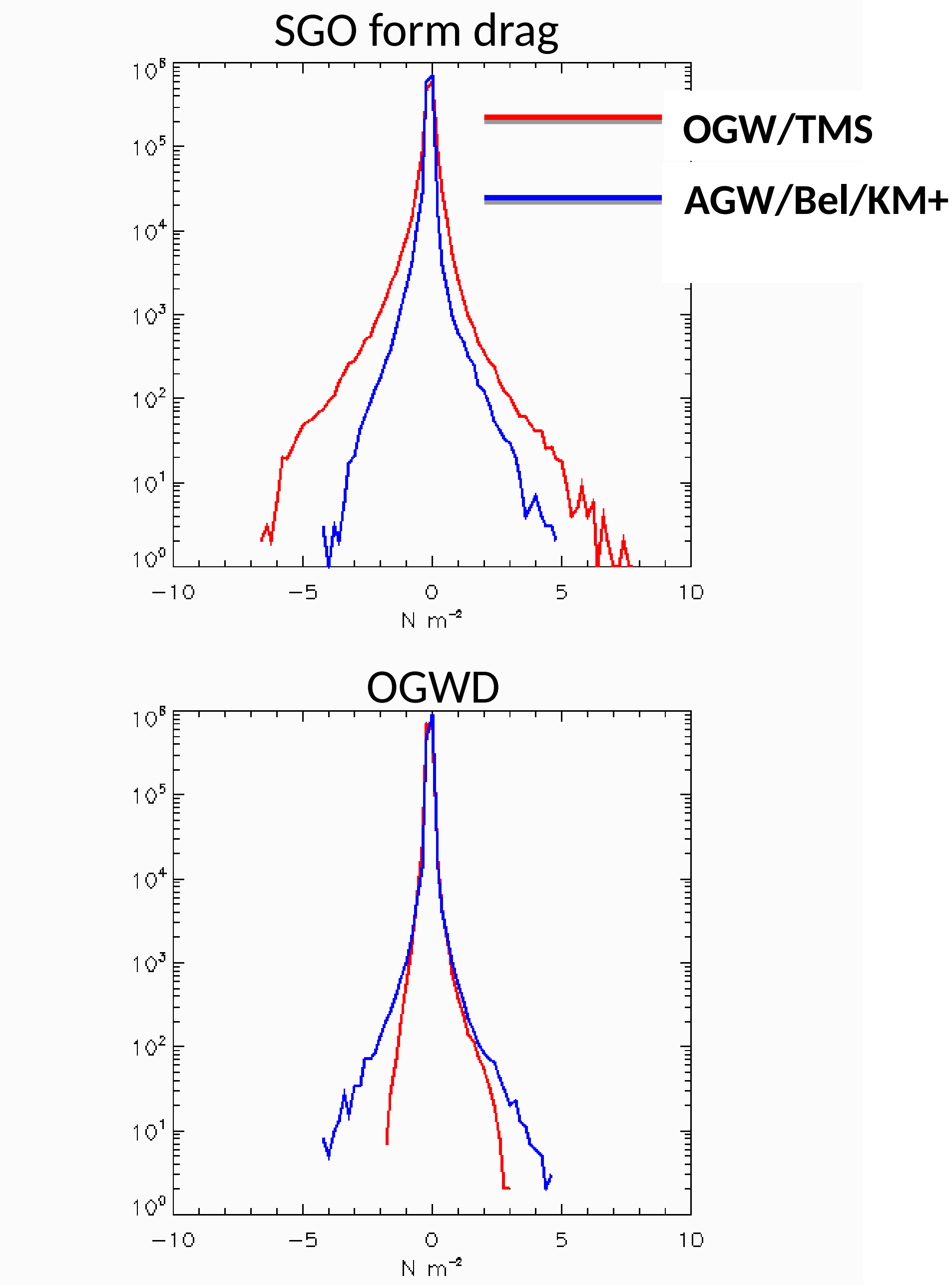
Annually averaged surface drag (total and components)







PDFs of monthly mean drag over land



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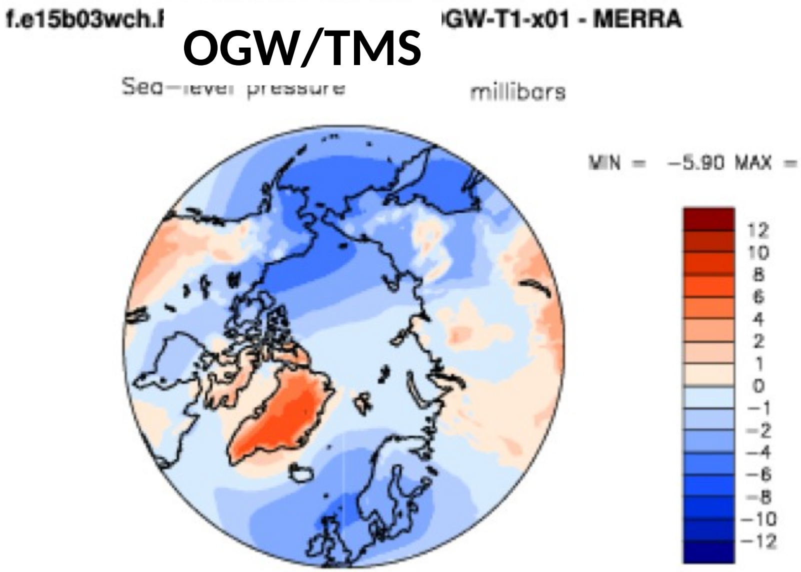
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GW-T1-x01 - MERRA
OGW/TMS
Sea-level pressure
millibars
MIN = -5.90 MAX =
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8
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-1
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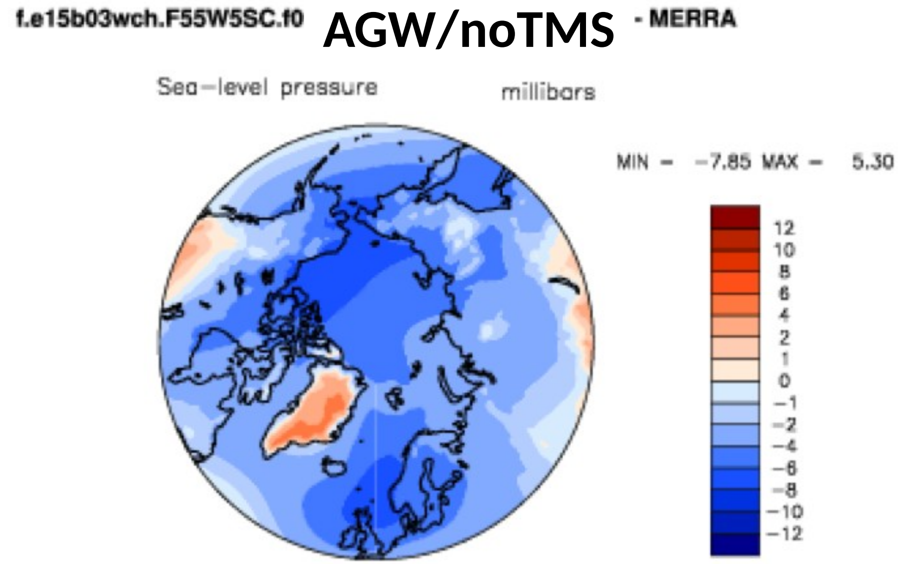
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AGW/noTMS
- MERRA
Sea-level pressure
millibars
MIN = -7.85 MAX = 5.30
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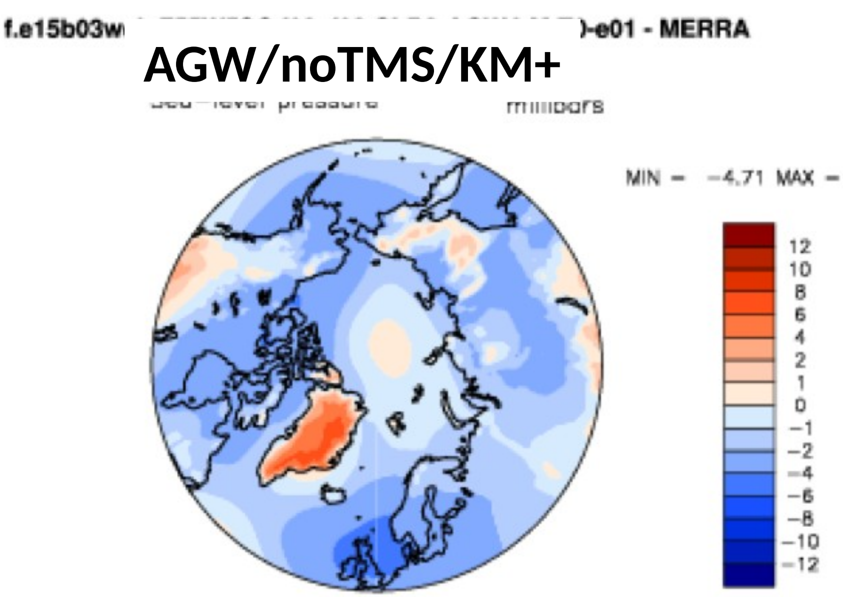
f.e15b03w
)-e01 - MERRA
AGW/noTMS/KM+
millibars
MIN = -4.71 MAX =
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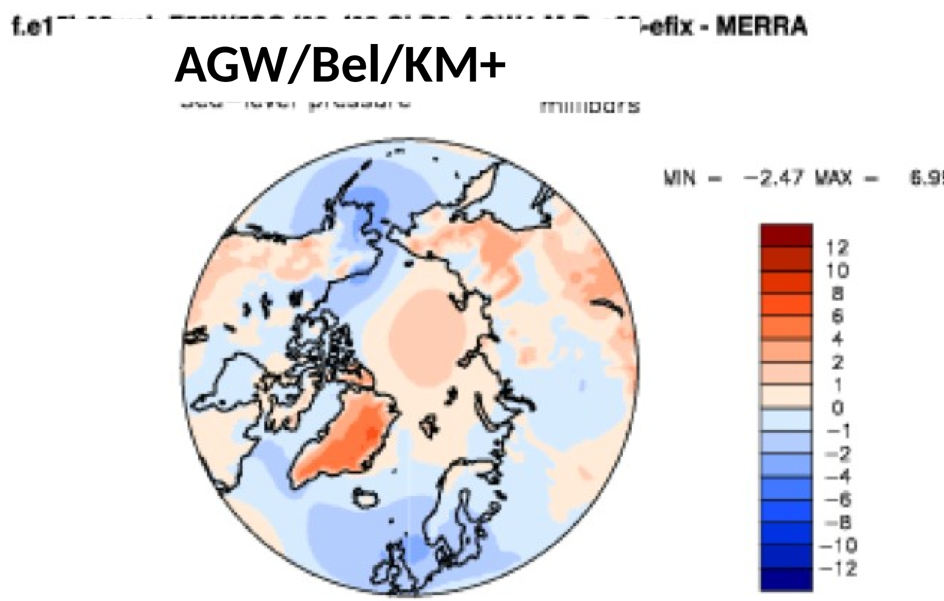
-12


-efix - MERRA
AGW/Bel/KM+
millibars
MIN = -2.47 MAX = 6.99
12
10
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4
2
1
0
-1
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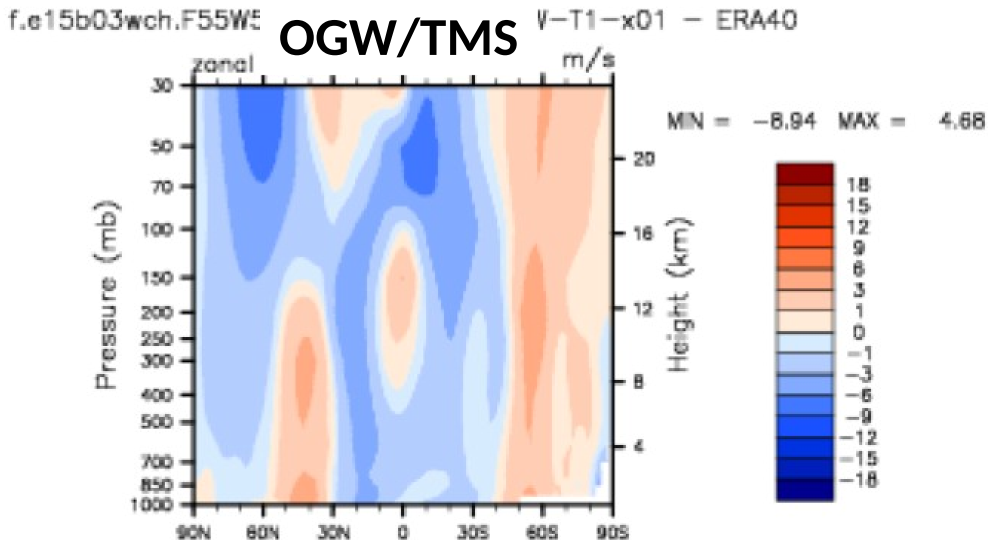
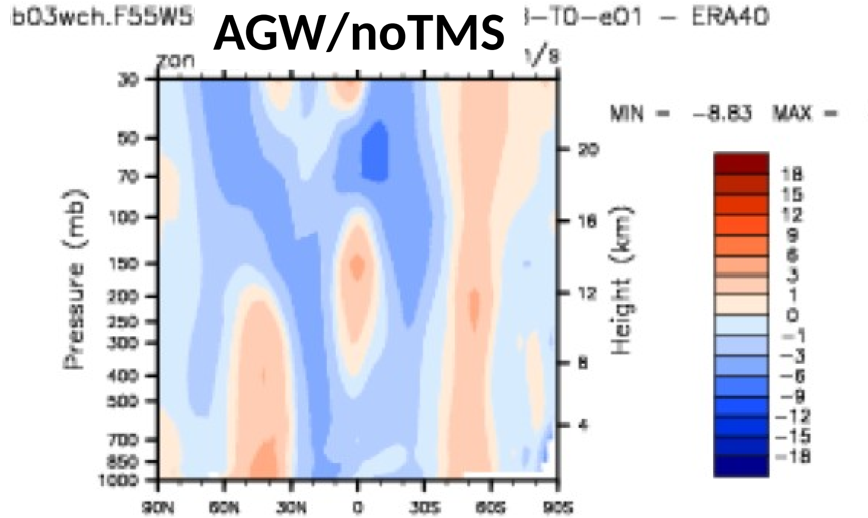
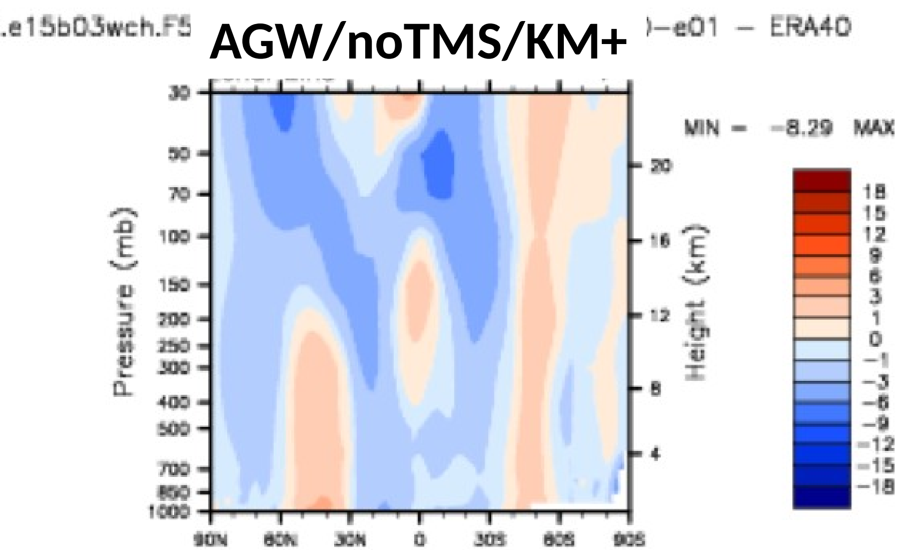
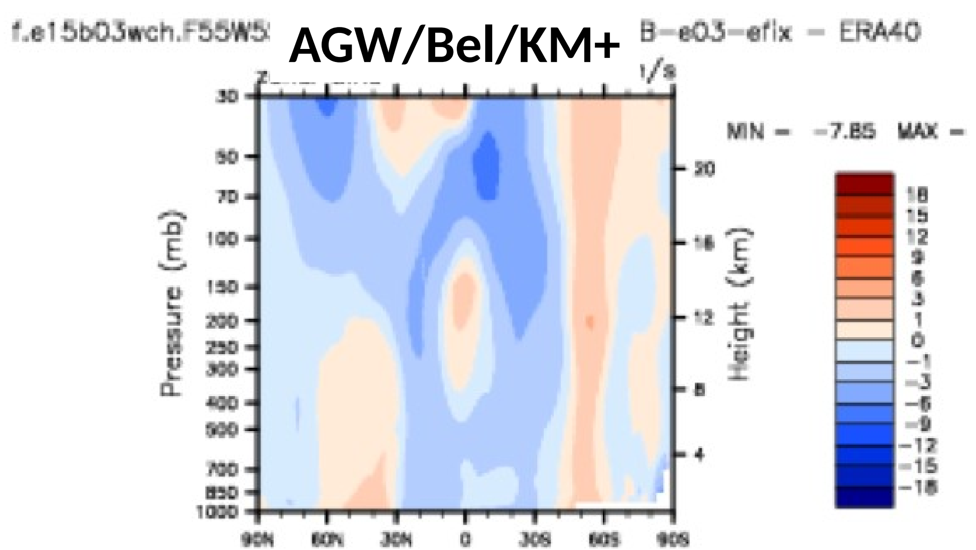
-12


f.e15b03wch.F55W5
OGW/TMS
V-T1-x01 - ERA40
zonal
m/s
MIN = -8.94 MAX = 4.68
Pressure (mb)
Height (km)
90N 60N 30N 0 30S 60S 90S
18 15 12 9 6 3 1 0 -1 -3 -6 -9 -12 -15 -18

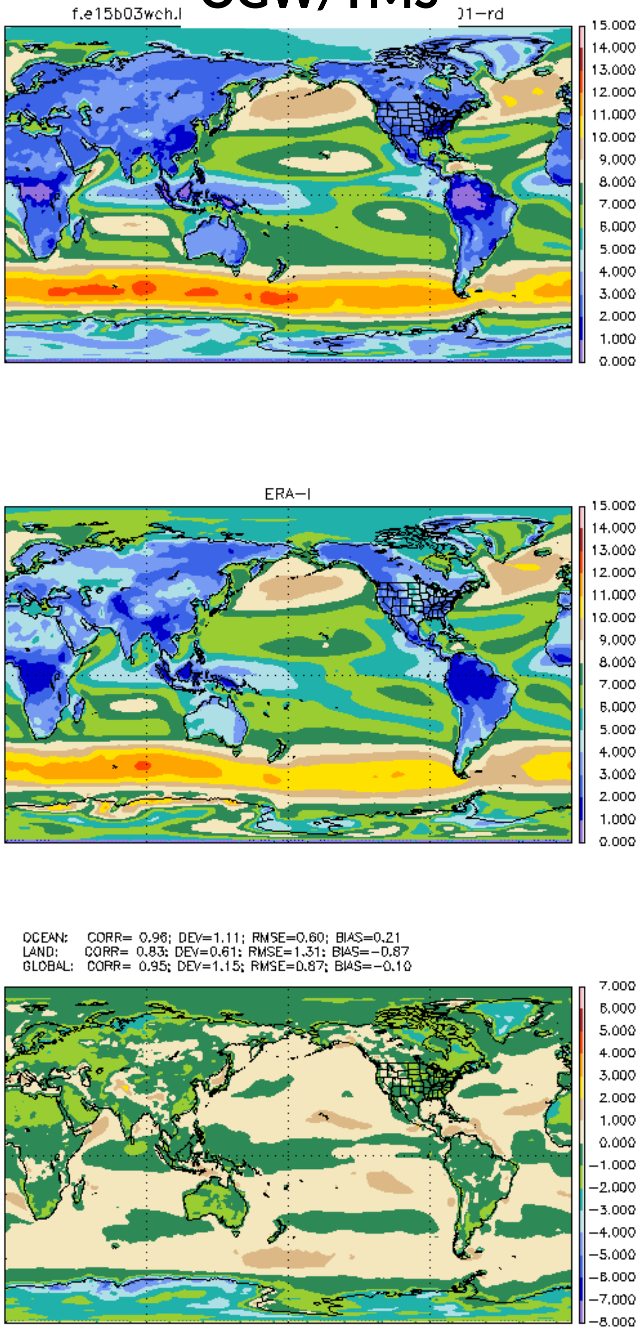

b03wch.F55W5
AGW/noTMS
-T0-e01 - ERA40
MIN = -8.83 MAX =
Pressure (mb)
Height (km)
90N 60N 30N 0 30S 60S 90S
18 15 12 9 6 3 1 0 -1 -3 -6 -9 -12 -15 -18


.e15b03wch.F5
AGW/noTMS/KM+
-e01 - ERA40
MIN = -8.29 MAX
Pressure (mb)
Height (km)
90N 60N 30N 0 30S 60S 90S
18 15 12 9 6 3 1 0 -1 -3 -6 -9 -12 -15 -18

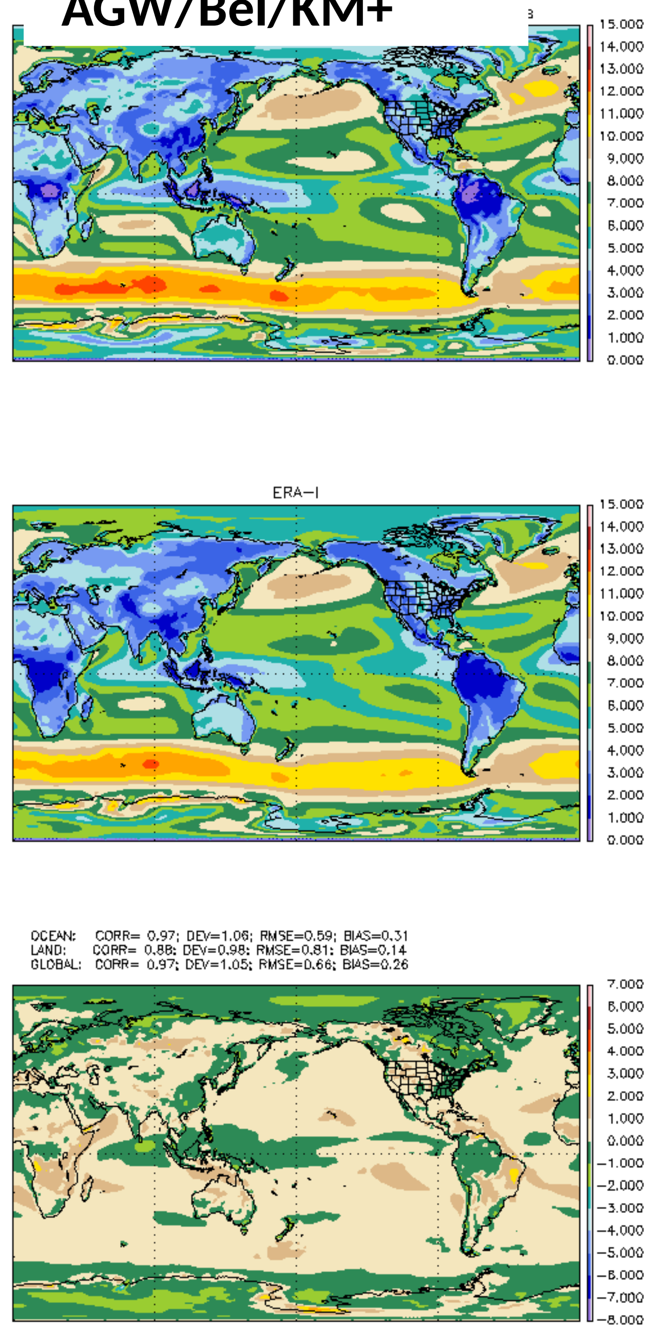

f.e15b03wch.F55W5
AGW/Bel/KM+
B-e03-eflx - ERA40
MIN = -7.85 MAX =
Pressure (mb)
Height (km)
90N 60N 30N 0 30S 60S 90S
18 15 12 9 6 3 1 0 -1 -3 -6 -9 -12 -15 -18

10m windspeed Annual mean

OGW/TMS



AGW/Bel/KM+

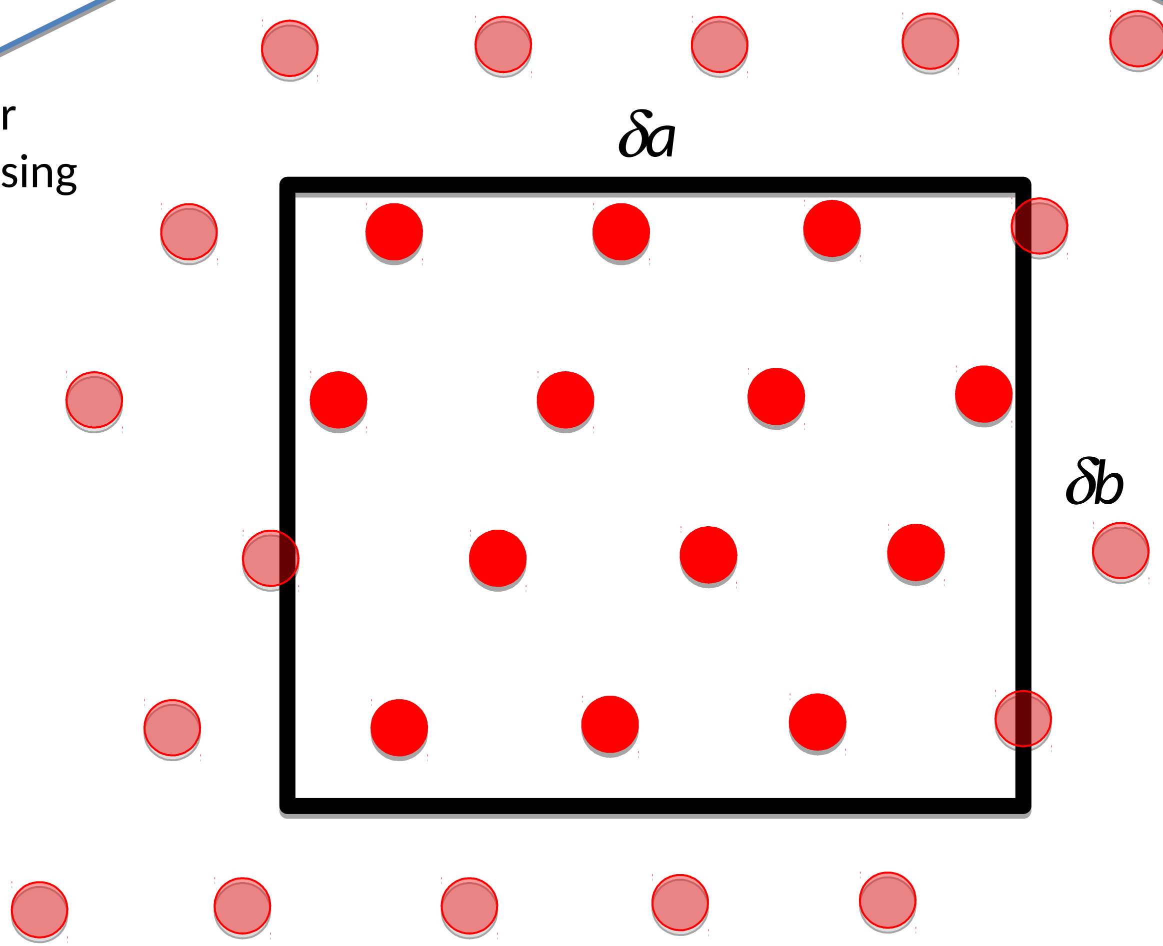


Data points from 1km GMTED or GTOPO30 datasets binned into “3km” cubed sphere grid boxes.   From solid red dots we obtain:

$$\bar{h}_{3km} = \frac{1}{n}\sum_{1}^{n} h_i \text{ and } \sigma_{3km} = \frac{1}{n}\sum_{1}^{n} (h_i - \bar{h}_{3km})^2$$

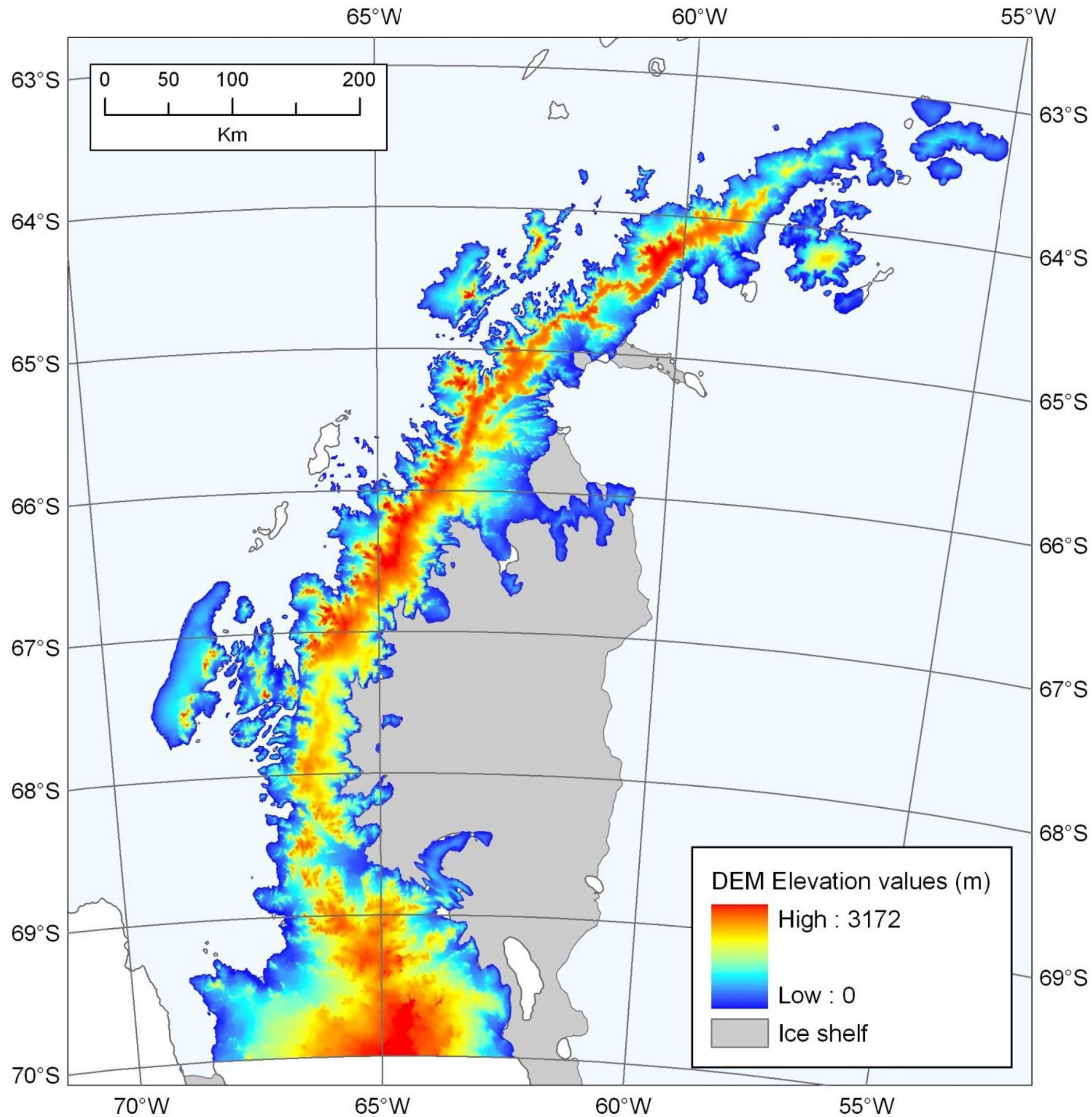
Further processing

Beljaars scheme



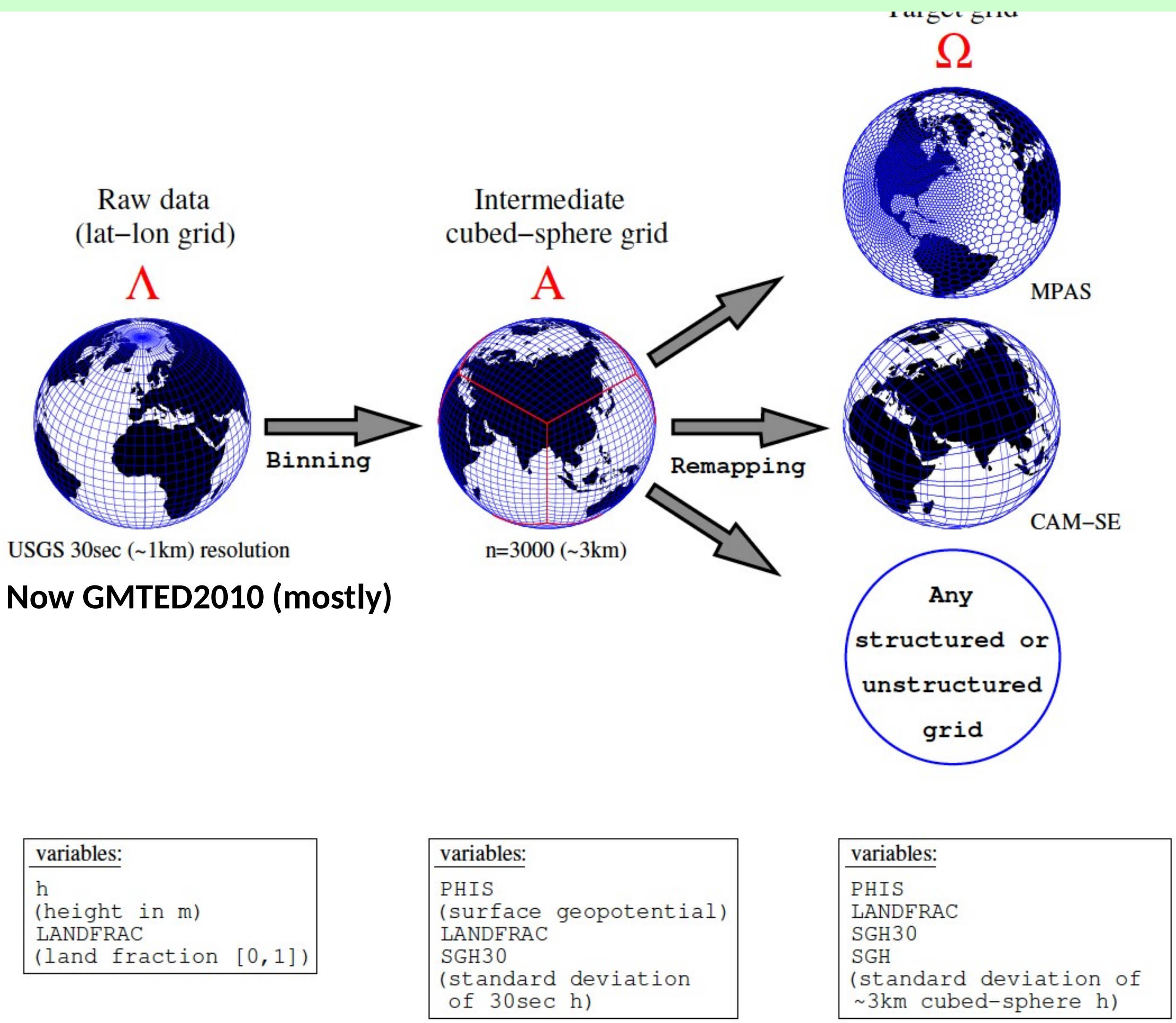
Antarctic Peninsula 100 m Digital Elevation Model Derived from ASTER GDEM

National Snow and Ice Data Center



http://nsidc.org/data/docs/agdc/nsidc0516-cook/

Topography Generation



Lauritzen et al. (2015, GMD)

Ridge-based orographic drag scheme with low-level nonlinearities

- Anisotropy
- Low-level processes (blocking)
- Multiple ridges