The Unified Gravity Wave Physics in the UFS

Michael Toy, NOAA GSL/CIRES

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4. NOAA/GSL and DTC
5. NCAR and DTC

UFS Webinar Series – July 1, 2021

Outline

- Theoretical background
- Description of the Unified Gravity Wave Physics (UGWP) parameterizations
- FV3GFS test results
- Future work
- Summary

Theoretical background: Topographic gravity waves

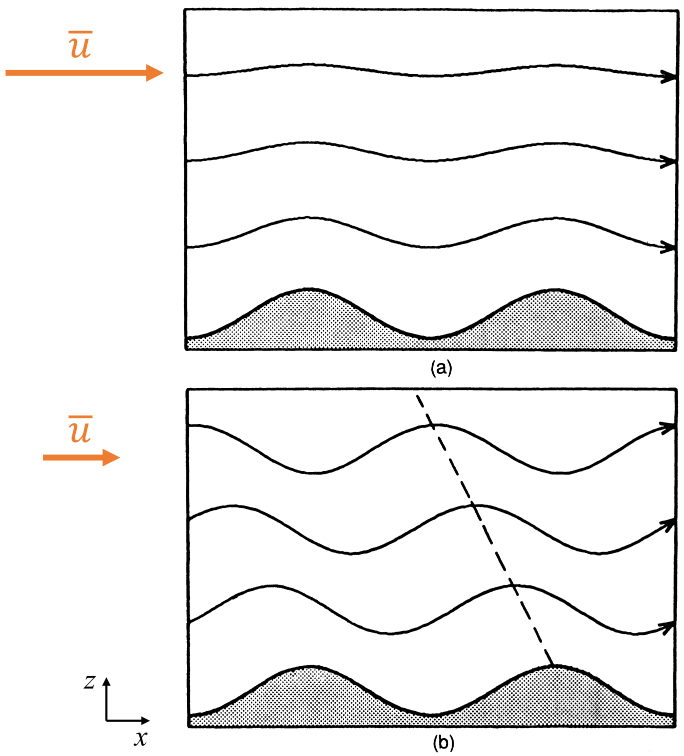


Figure from Holton (2004)

Linearized, Steady-state, Nonhydrostatic, Boussinesq equations give the wave equation for perturbation vertical velocity:

$$\left(\frac{\partial^2 w'}{\partial x^2}+\frac{\partial^2 w'}{\partial z^2}\right)+\frac{N^2}{\overline{u}^2}w'=0$$

Assume:

$$w'=\mathrm{Re}\left[\hat{w}e^{i(kx+mz)}\right]$$

This gives the dispersion relationship:

$$m^2=\frac{N^2}{\overline{u}^2}-k^2$$

( )' = perturbations from basic state
$\overline{u}$ = mean zonal wind
N = Brunt Väisälä frequency
m = vertical wave number
k = horizontal wave number

Theoretical background: Topographic gravity waves

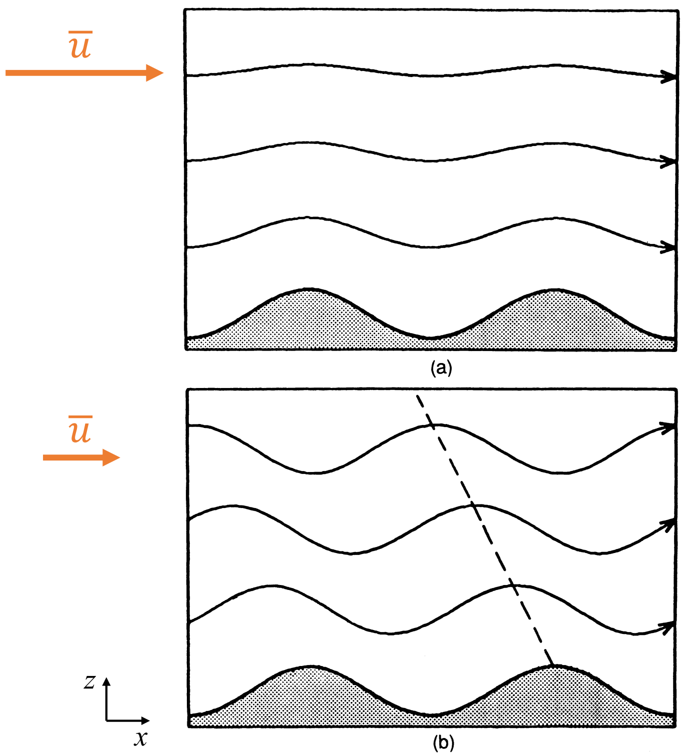


Figure from Holton (2004)

Dispersion relationship: $m^2 = \frac{N^2}{\overline{u}^2} - k^2$

( )' = perturbations from basic state
$\overline{u}$ = mean zonal wind
N = Brunt Väisälä frequency
m = vertical wave number
k = horizontal wave number

Case "a":
Vertically trapped waves

$$\frac{N^2}{\overline{u}^2} < k^2 \rightarrow m^2 < 0 \rightarrow \boxed{w' = \hat{w}e^{ikx}e^{-m_i z}}$$

Case "b":
Vertically propagating waves

$$\frac{N^2}{\overline{u}^2} > k^2 \rightarrow m^2 > 0 \rightarrow \boxed{w' = \hat{w}e^{i(kx+mz)}}$$

Theoretical background: Topographic gravity waves

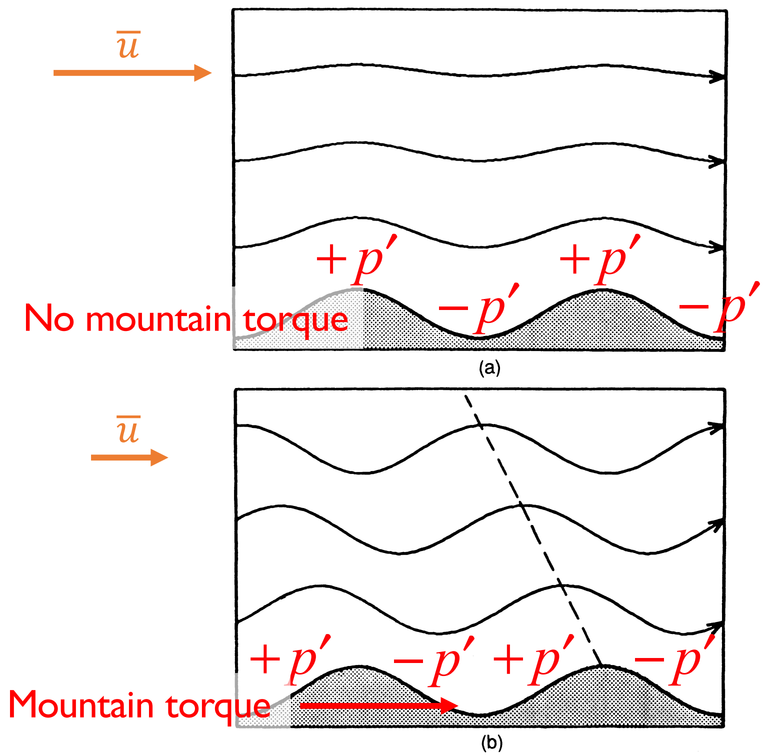


Figure from Holton (2004)

Case "a":
Vertically trapped waves

Perturbation zonal wind = $u' \propto -iw'$ (90° phase difference)

Momentum flux (wave stress) = $\bar{\rho}\overline{u'w'} = 0$ No drag!

Case "b":
Vertically propagating waves

Perturbation zonal wind = $u' \propto -w'$ (180° phase difference)

Momentum flux (wave stress) = $\bar{\rho}\overline{u'w'} < 0$

Theoretical background: Topographic gravity waves

Dispersion relationship: $m^2 = l^2 - k^2,$

where $l = \dfrac{N}{\overline{u}} =$ Scorer parameter

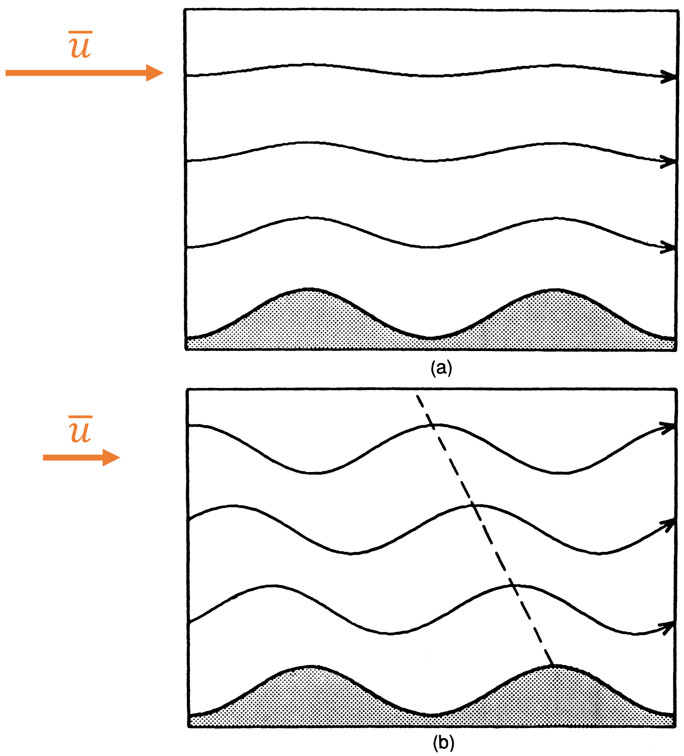


Figure from Holton (2004)

Case "a":

Vertically trapped waves – **no drag**

$$l^2 < k^2$$

For given stability, $\overline{u}$ large and/or k large (narrow hills)

Case "b":

Vertically propagating waves – **drag forces exist**

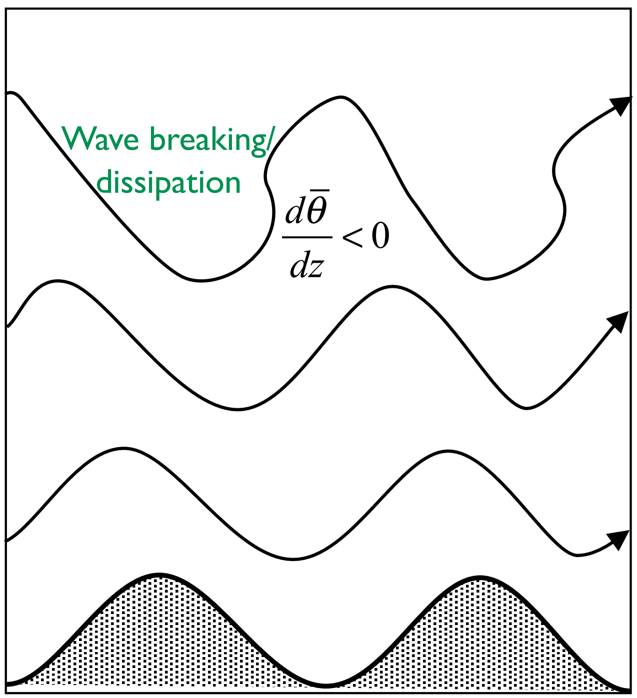
$$l^2 > k^2$$

Surface wave stress: $\tau \cong \dfrac{1}{2}\rho k H^2 N U$

For given stability, $\overline{u}$ small and/or k small (wide hills)

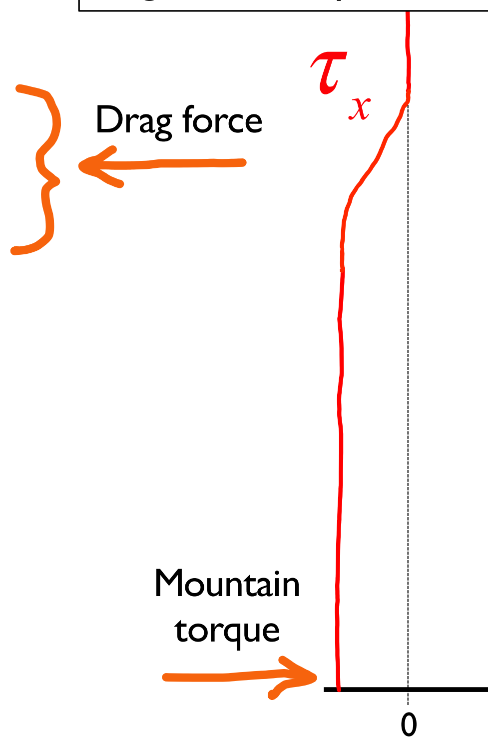
Theoretical background: Topographic gravity waves

Constant Scorer-parameter profile, e.g., $\overline{u}, N$ = constant



How and where is gravity wave drag force imparted on the flow?

In compressible atmosphere, wave amplitude increases with height as density decreases until waves overturn and break



Wave stress: $\tau_x = \overline{\rho}\,\overline{u'w'}$

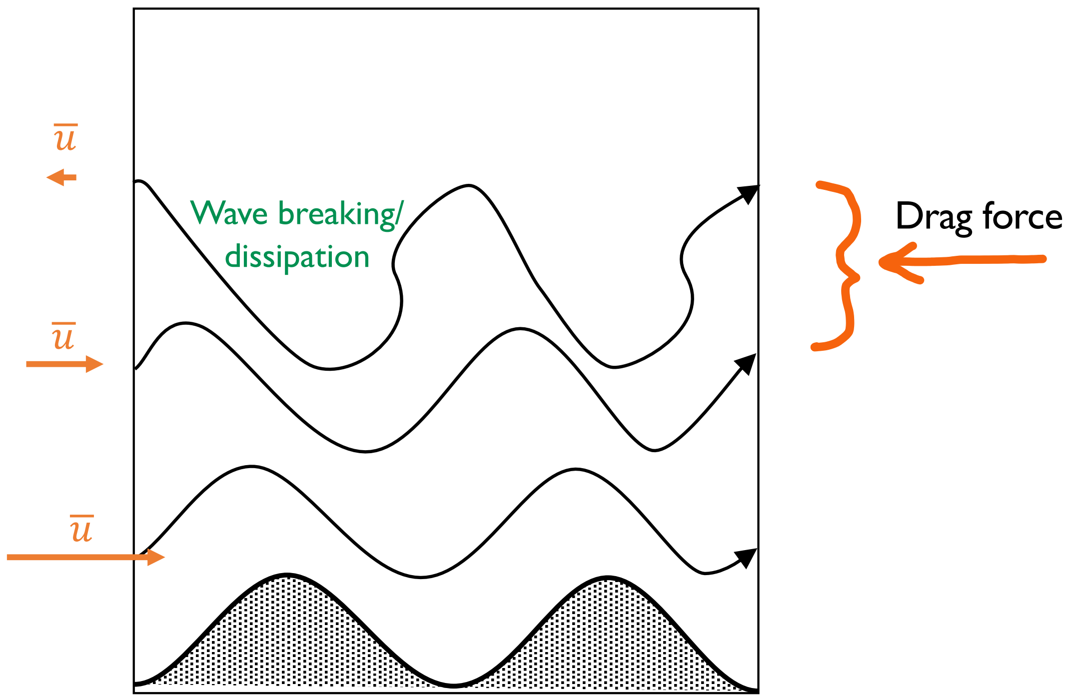
(vertical momentum flux, N/m^2)

Drag: $\left(\frac{\partial U}{\partial t}\right)_{\mathrm{drag}} = -\frac{1}{\overline{\rho}}\frac{\partial \tau_x}{\partial z}$

Theoretical background: Topographic gravity waves

How and where is gravity wave drag force imparted on the flow?

Increasing Scorer-parameter with height, e.g., negative windshear



Negative wind shear can accelerate wave overturning, lowering the height at which it may occur ("critical level" where $\overline{u} = 0$)

Note that horizontal wavenumber (k) of topography can effect the height at which waves overturn:

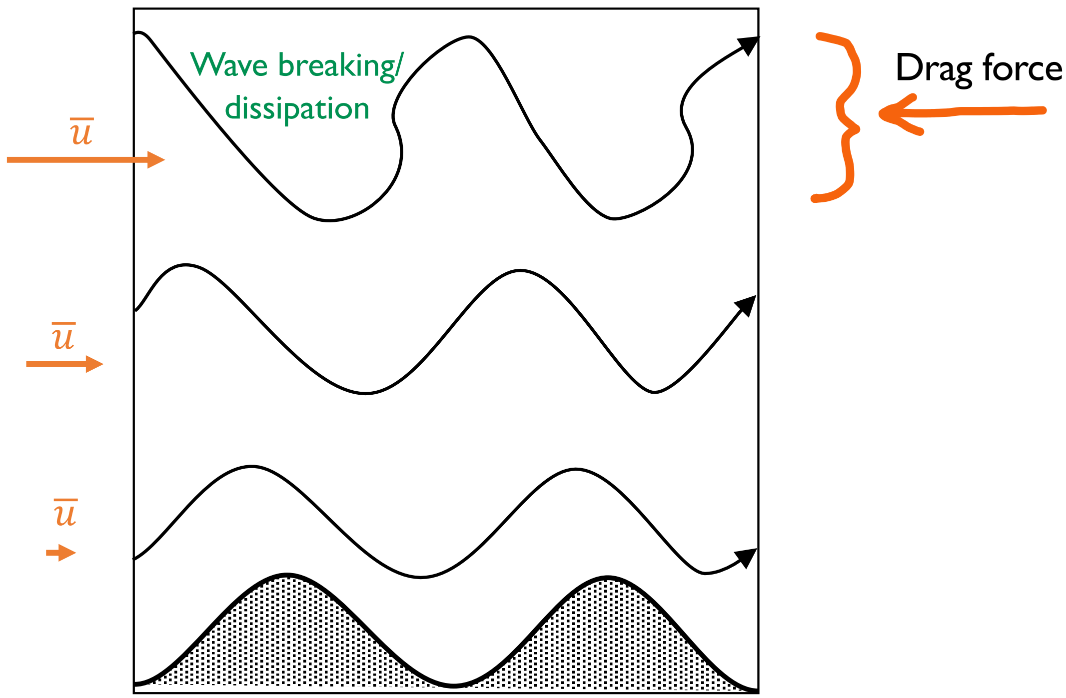
$$m^2 = l^2 - k^2$$

Decreasing *k* increases *m* which increases likelihood of having $\frac{d\overline{\theta}}{dz} < 0$ somewhere within the wave

Theoretical background: Topographic gravity waves

How and where is gravity wave drag force imparted on the flow?

Decreasing Scorer-parameter with height, e.g., positive windshear



Positive wind shear can lead to some waves to be trapped if their wavenumber (k) exceeds a certain value such that:

$$m^2 = l^2 - k^2 < 0$$

Waves with smaller wavenumber (k) propagate to a height where they would eventually break.

Theoretical background: Low-level flow blocking

Flow makes it over mountain
K.E. > P.E.

Flow is blocked
K.E. < P.E.

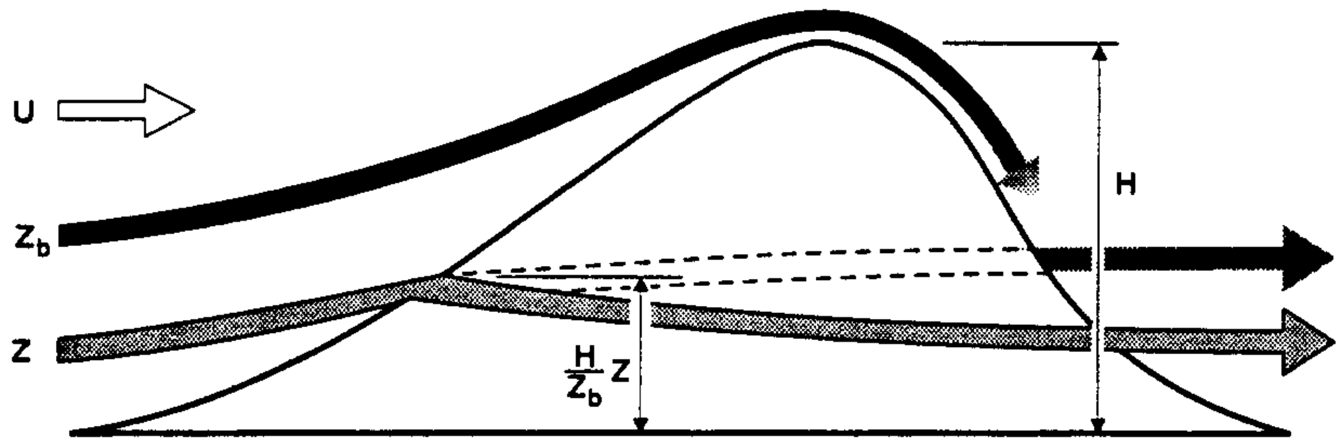
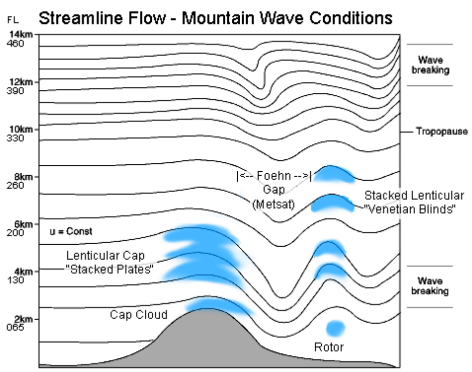


Figure from Lott and Miller (QJRMS, 1997)

Surface stress = $\tau \propto \rho z_b \overline{u}^2$

Overview of the Unified Gravity Wave Physics (UGWP) parameterizations

Large-scale gravity wave drag



Low-level flow blocking

Non-stationary gravity wave drag

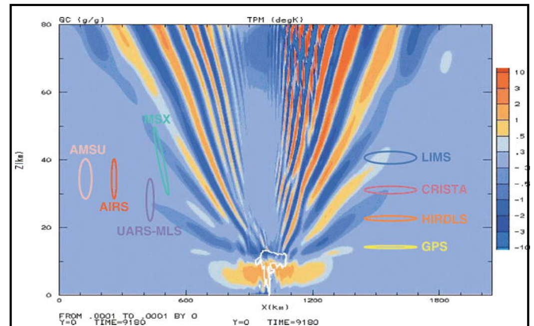
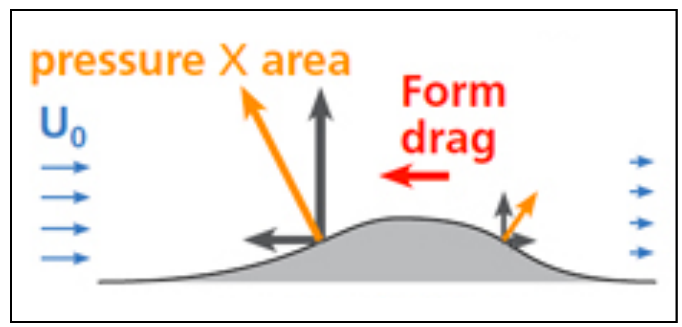


Figure from Alexander and Barnet (JAS,2007)

Small-scale gravity wave drag

Two new schemes from GSL drag suite

Turbulent orographic form drag

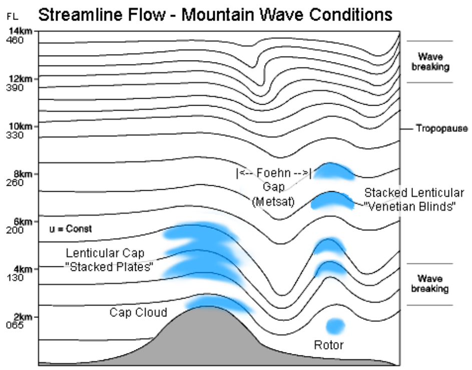


UGWP v1 is called by the Common Community Physics Package (CCPP) "ugwpv1_gsldrag" scheme

Overview of the Unified Gravity Wave Physics (UGWP) parameterizations

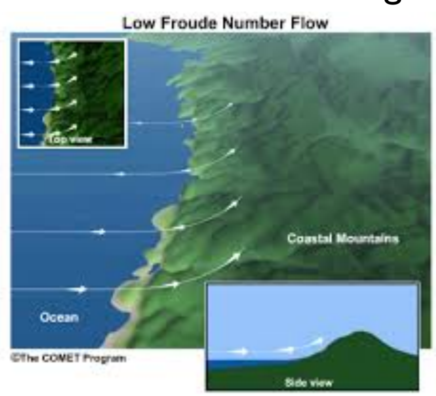
GFS physics source code (version 15 and prior)

Large-scale gravity wave drag



Kim and Arakawa (JAS, 1995)

Low-level flow blocking



Lott and Miller (QJRMS, 1997)

gwdps.f

Non-stationary gravity wave drag

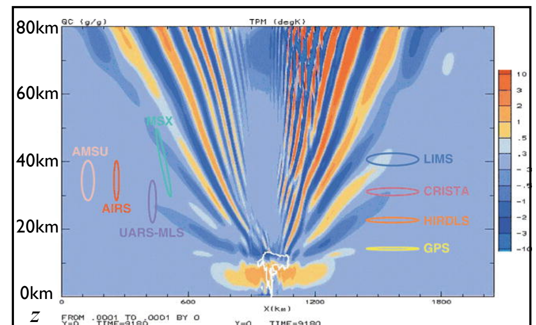


Figure from Alexander and Barnet (JAS,2007)

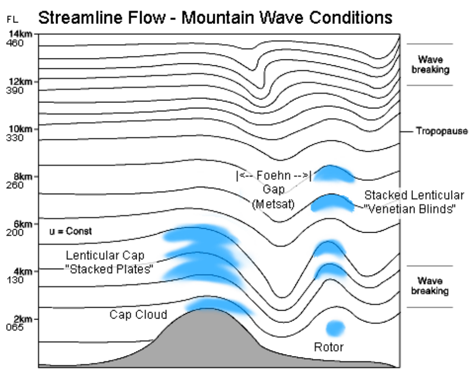
Chun and Baik (JAS, 1998)

gwdc.f

Overview of the Unified Gravity Wave Physics (UGWP) parameterizations

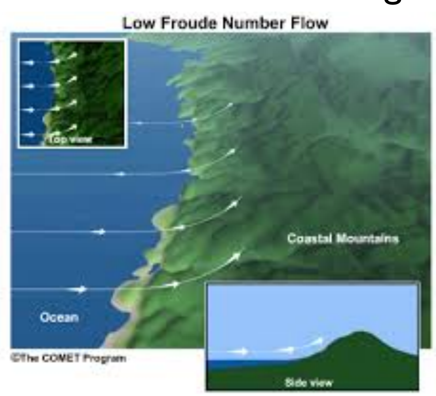
UGWP_v1 CCPP suite: ugwpv1_gsldrag.F90

Large-scale gravity wave drag



Kim and Doyle (JAS, 1995);
Choi and Hong (JGR, 2015)

Low-level flow blocking



Kim and Doyle (JAS, 1995)

drag_suite.F90
(RAP/HRRR/WRF-ARW implementation)

Non-stationary gravity wave drag

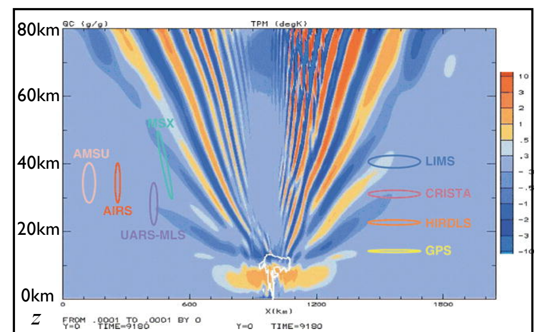


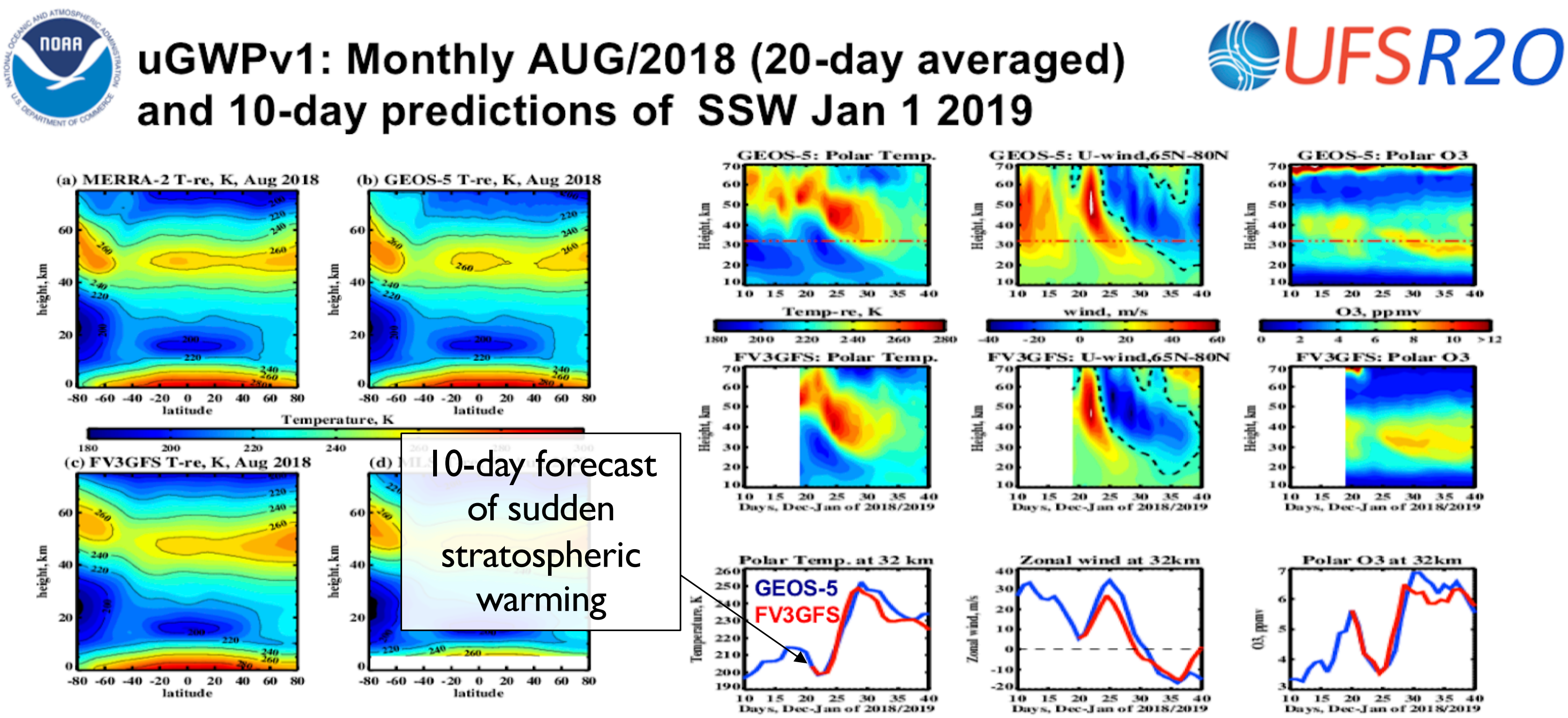
Figure from Alexander and Barnet (JAS,2007)

Yudin (2020)

Cires_ugwpv1_solv2.F90

Improvements to stratospheric forecasts: UGWP v1 non-stationary GWD

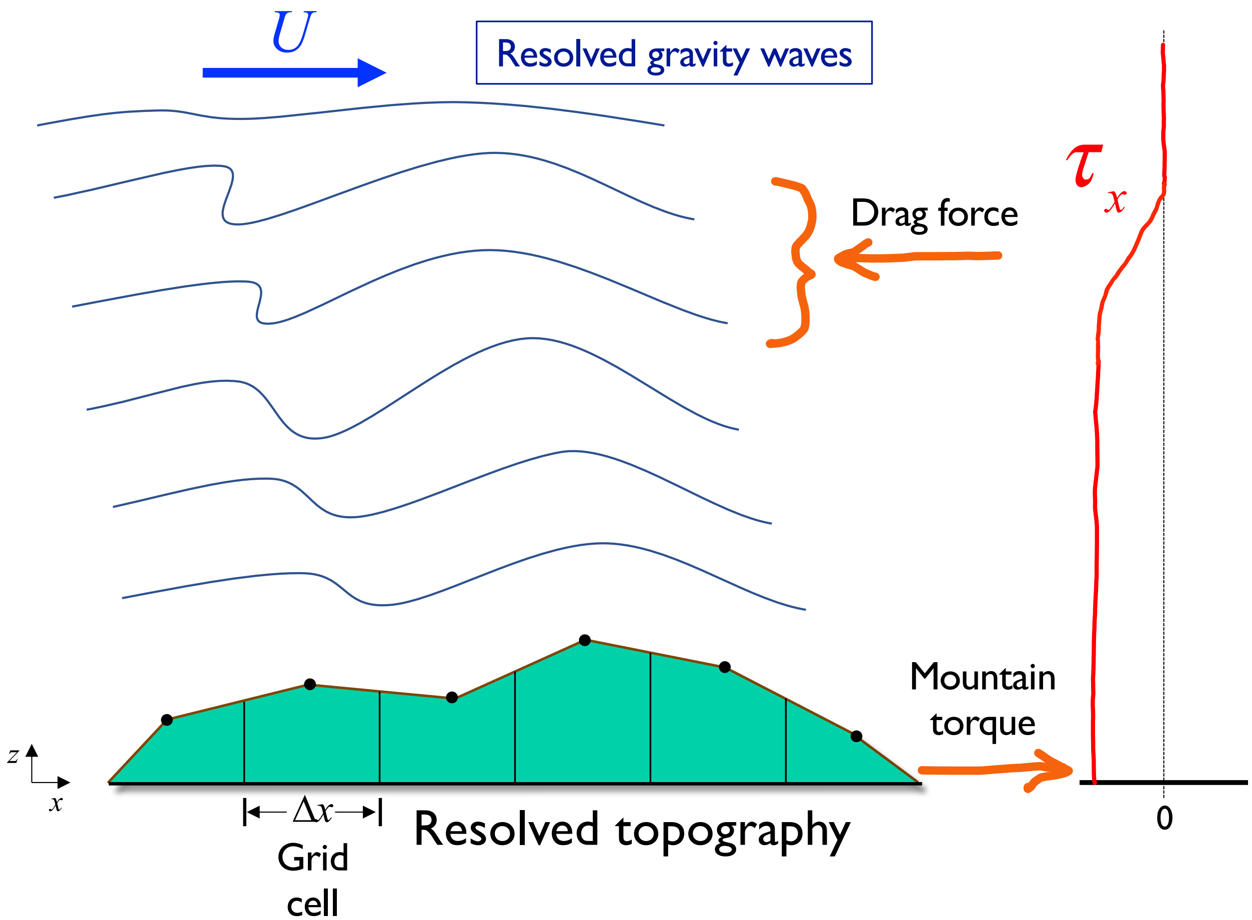
uGWPv1: Monthly AUG/2018 (20-day averaged) and 10-day predictions of SSW Jan 1 2019



- Left plate: FV3GFS (c) monthly averaged T-predictions vs MERRA-2 (a), GEOS-5 (b), and MLS data (d)
- Right plate: Predicting (30-day run) the SSW Jan 1 2020 by FV3GFS (10 days before the SSW onset) and GEOS-5 analyses

Slide courtesy of Valery Yudin

Large-scale gravity wave drag parameterization

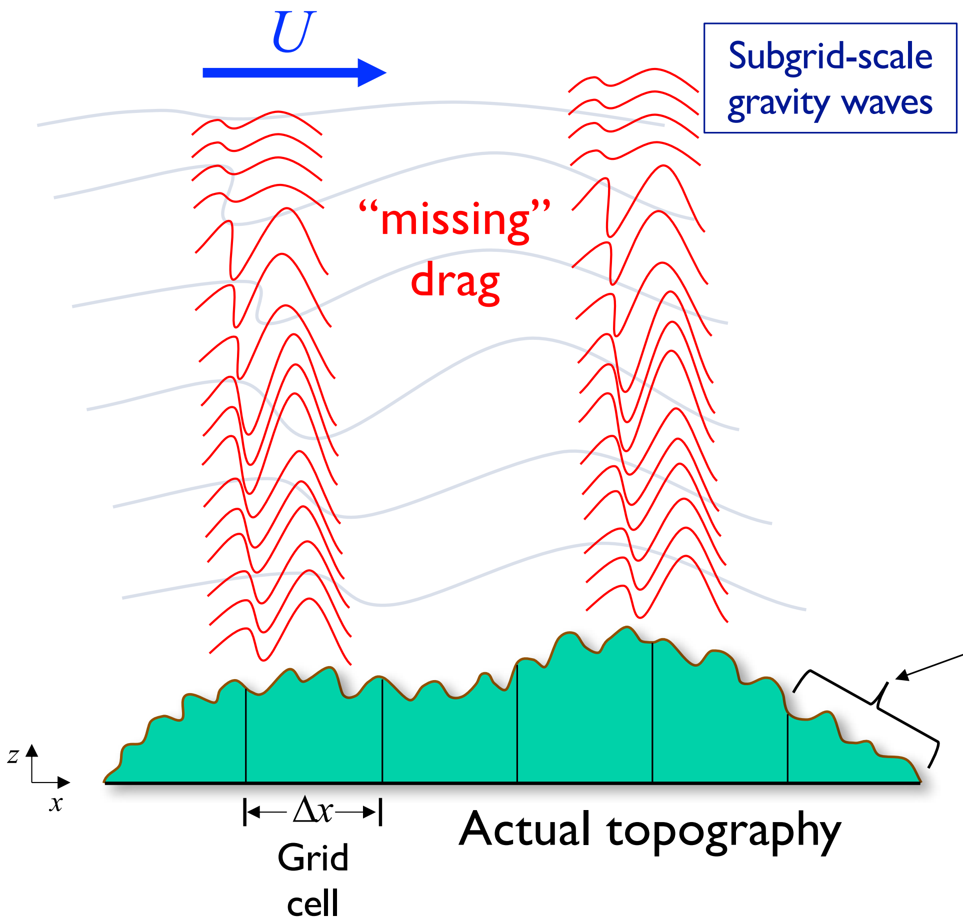


Wave stress: $\tau_x = \bar{\rho}\,\overline{u'w'}$

(vertical momentum flux, N/m²)

Drag: $\left(\frac{\partial U}{\partial t}\right)_{\text{drag}} = -\frac{1}{\bar{\rho}}\frac{\partial \tau_x}{\partial z}$

Large-scale gravity wave drag parameterization



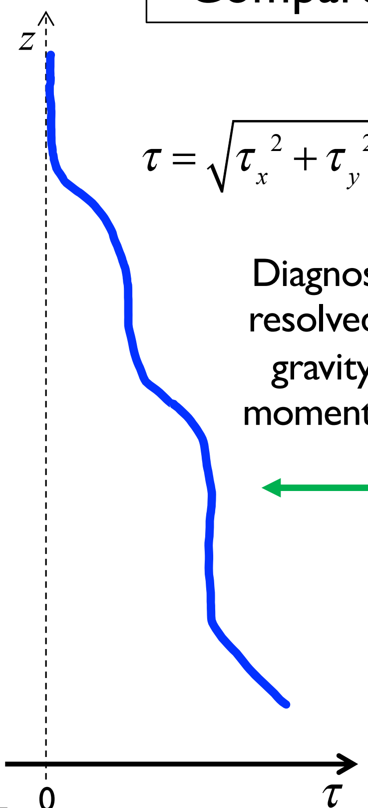
Parameterized wave stress: $\tau_x = \bar{\rho}\,\overline{u'w'}$

Parameterized drag: $\left(\frac{\partial U}{\partial t}\right)_{\text{drag}} = -\frac{1}{\bar{\rho}}\frac{\partial \tau_x}{\partial z}$

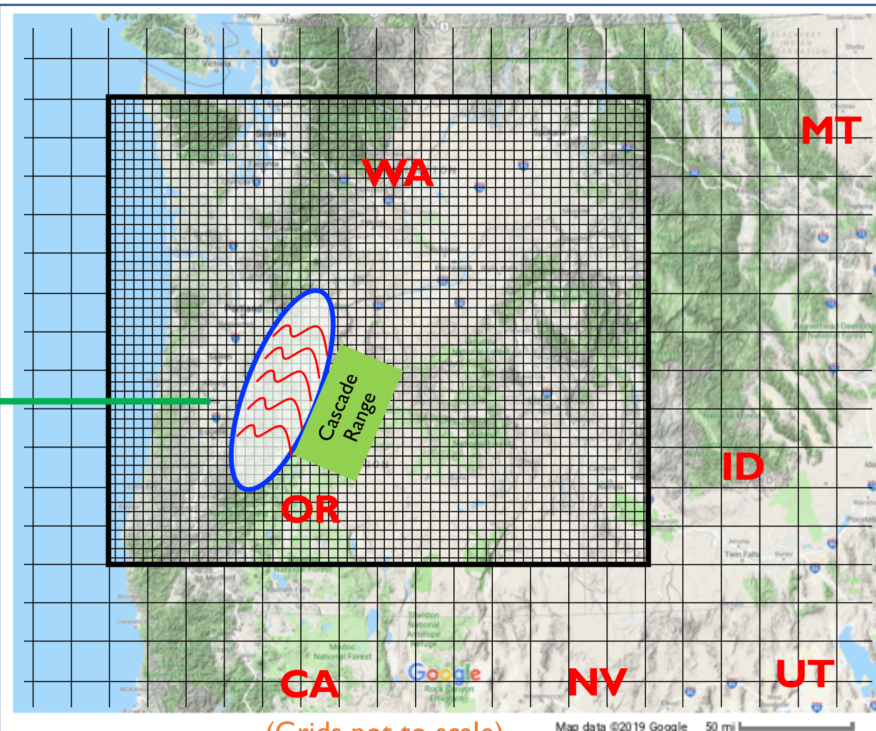
Standard deviation of subgrid topography within each grid cell is used as proxy for mountain height for surface stress calculation

Large-scale gravity wave drag parameterization

Compare parameterized wave stress to "true" stresses at various grid sizes



Diagnose fully-resolved "true" gravity wave momentum flux



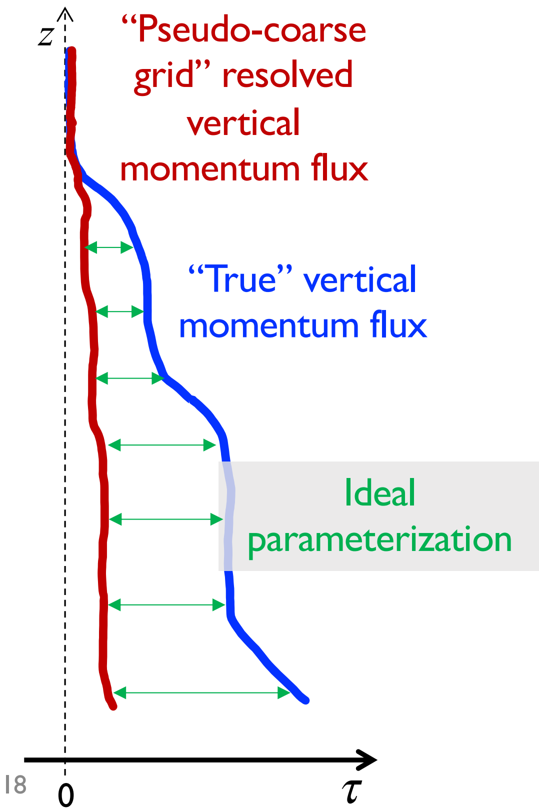
(Grids not to scale)

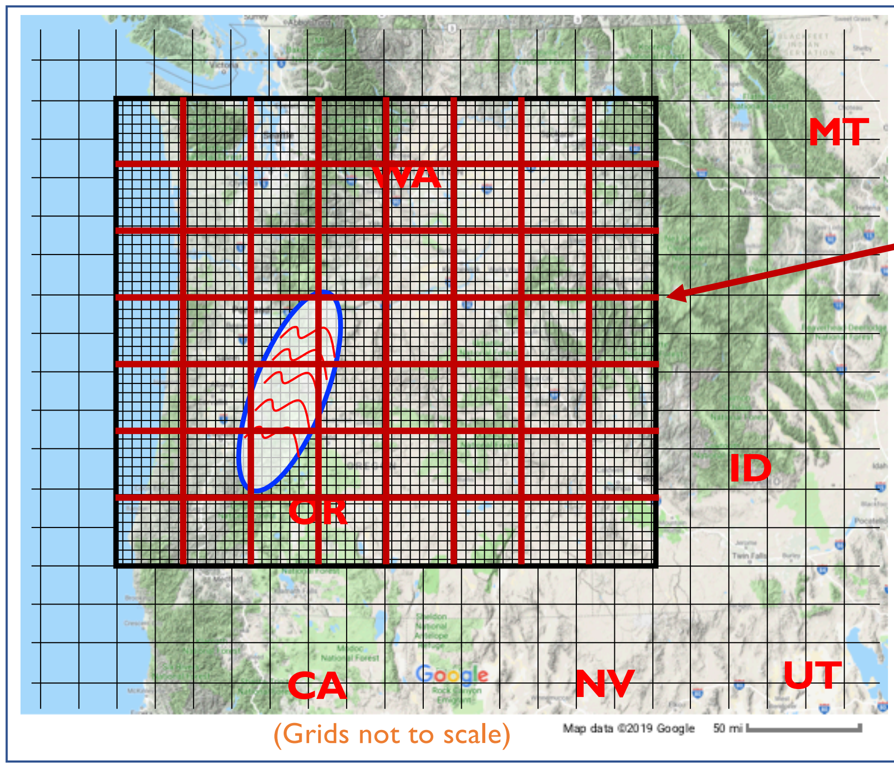
Used high-resolution WRF reforecasts run during the Wind Forecast Improvement Project 2 (WFIP2)

- Field campaign to improve wind forecasts over complex terrain
- 750m grid nested within 3km HRRR grid

Large-scale gravity wave drag parameterization

Compare parameterized wave stress to "true" stresses at various grid sizes





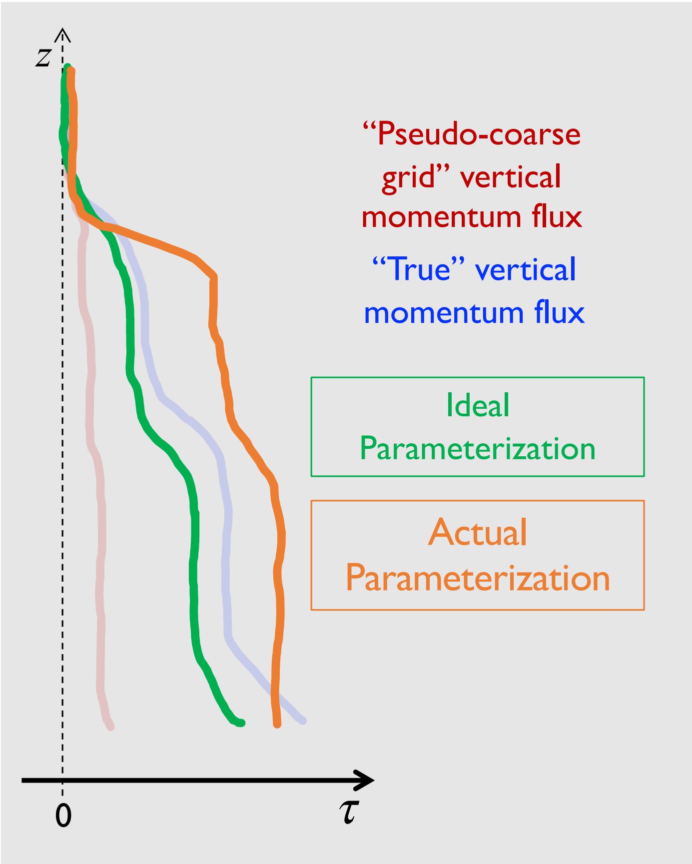
Average fine-grid variables

$$\left(\rho,\theta,u,v,w,\text{etc}\right)$$

onto a coarse grid, giving a "pseudo-coarse grid" model result, and calculate resolved GW momentum flux

Define an "ideal parameterization" as the difference between "true" and "pseudo-coarse" momentum fluxes

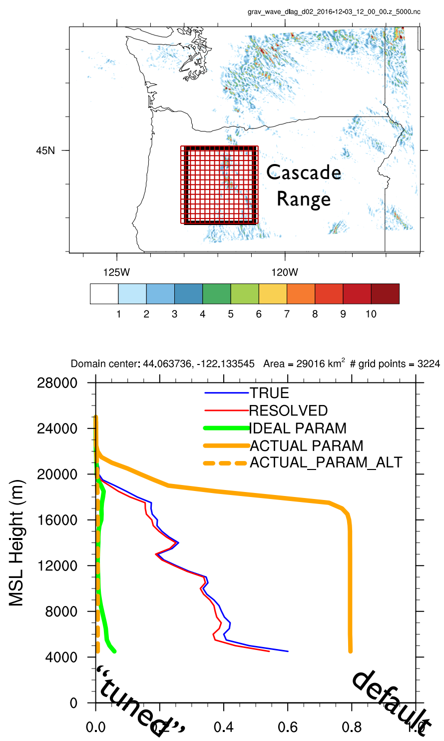
Large-scale gravity wave drag parameterization



Compare ideal parameterization to actual parameterization.

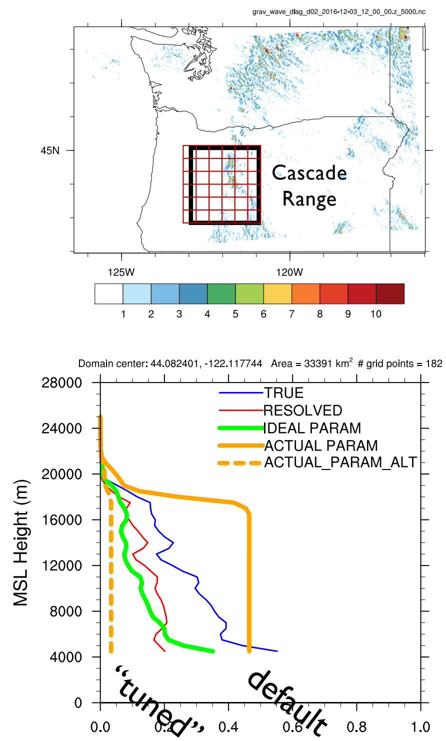
Large-scale gravity wave drag parameterization

3km HRRR grid



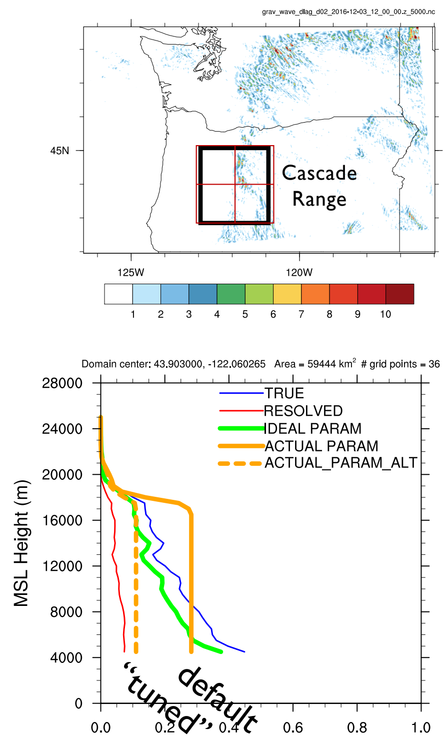
Parameterization not needed

13km RAP grid



50/50 parameterized/resolved

40km RAP-like grid



GWD almost fully parameterized

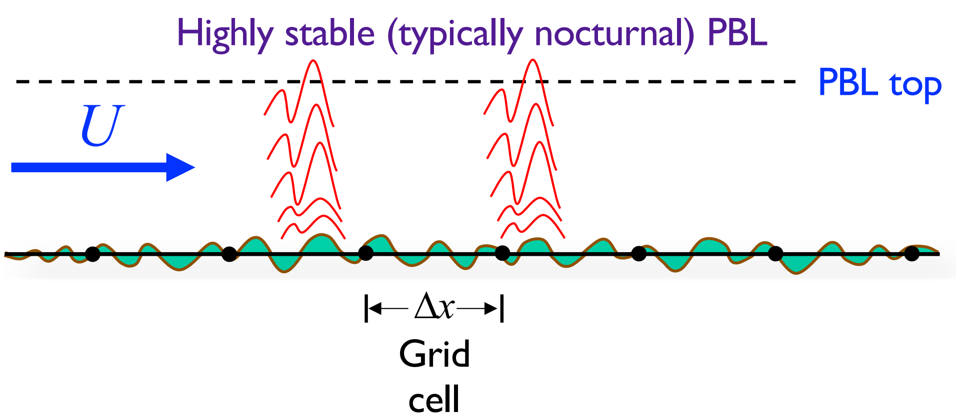
- GFS "tuning" is reasonable
- Gray zone for LS-GWD parameterization ~5km - ~50km (for this geographic location)

- Parameterized flux profiles constant below $z \cong 16$km (compare to "ideal" parameterization)
- Issue with considering only one horizontal wavelength?

“Small-scale” GSL drag suite schemes

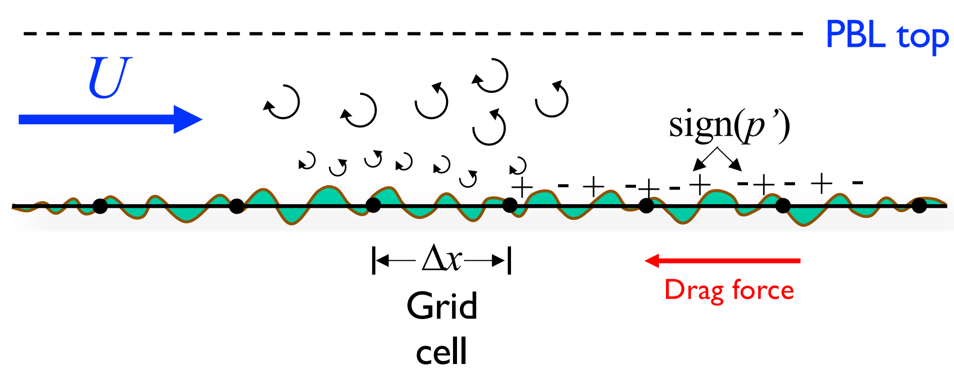
Small-scale gravity wave drag (SSGWD) in stable PBLs
Tsiringakis et al. (2017); Steenveld et al. (2008)

- Highly stable PBL allows vertical propagation of gravity waves at smaller horizontal scales
- Drag force imparted throughout PBL depth
- Used for grid resolutions > 1 km



Turbulent orographic form drag (TOFD)
Beljaars et al. (2004)

- Positively correlated turbulent pressure perturbations and terrain slope cause an opposing drag force (Note: This is not gravity wave drag)
- Drag force decays exponentially with height (e-folding height is ~ 1.5 km)
- Terrain height is band-pass filtered to remove horizontal variations >20 km and <2 km before calculating the standard deviation of the subgrid topography
- Used for grid resolutions > 1 km



"Small-scale" GSL drag suite schemes

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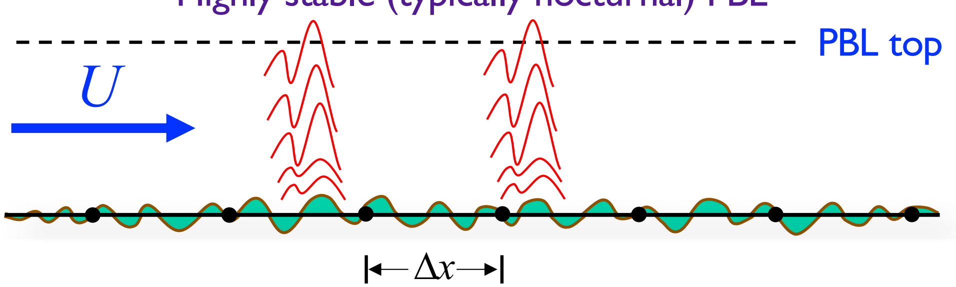

From Tsiringakis et al. (QJRMS, 2017):

Surface stress:
$$\tau_0 = \begin{cases} \frac{1}{2}\rho_0 k H^2 N \bar{u}, & \text{if } \frac{N}{\bar{u}} \geq k \quad \text{Vertical propagation} \\ 0, & \text{if } \frac{N}{\bar{u}} < k \quad \text{Trapped waves} \end{cases}$$

Vertical stress profile: $\tau(z) = \tau_0 \left(1 - \frac{z}{h}\right)^2$ h = PBL height

Where: $H = 2\sigma_h$ (2 x std dev of subgrid topography)

$k = \frac{(1 + L_x)^{1+OA}}{\lambda_{\text{eff}}}$ Horizontal wave number of topog.

L_x, OA and λ_{eff} Parameters from Kim and Doyle (2005)

"This scheme can be thought of as an extension of the Kim and Arakawa scheme to within the PBL."
-- paraphrasing Tsiringakis et al. (2017)

(In the future the schemes should be unified.)

"Small-scale" GSL drag suite schemes

Wind speed tendency from drag:

$$\left(\frac{\partial|\mathbf{U}|}{\partial t}\right)_{\mathrm{TOFD}} = -\alpha\beta C_{\mathrm{md}} C_{\mathrm{corr}} |\mathbf{U}(z)| \mathbf{U}(z) 2.109\, \mathrm{e}^{-(z/1500)^{1.5}} a_2 z^{-1.2}$$

30sec topographic data is band-passed filtered before calculating subgrid standard deviation:

1344 A. C. M. BELJAARS *et al.*

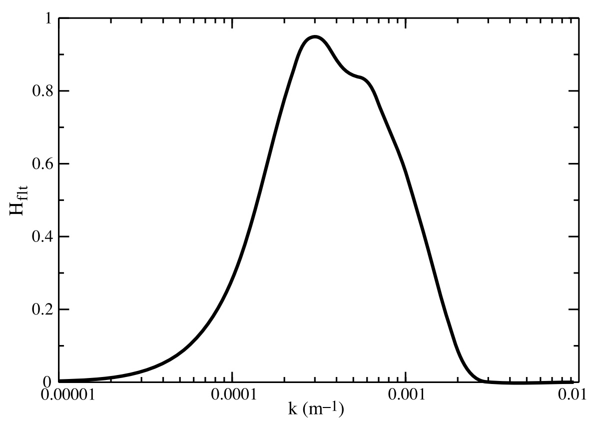

Figure A.2. Spectral filter corresponding to difference of two smoothing operations with: $\Delta_1 = 2$ km, $\Delta_2 =$ 20 km, $\delta_1 = \delta_2 = 1$ km.

Turbulent orographic form drag (TOFD)
Beljaars et al. (2004)

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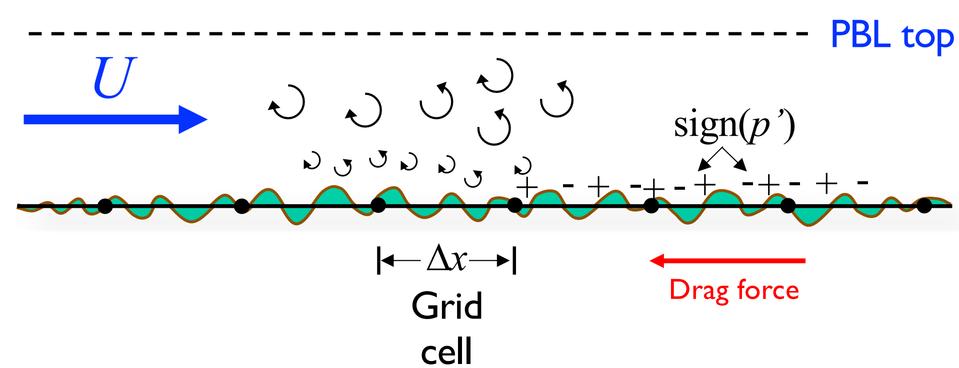
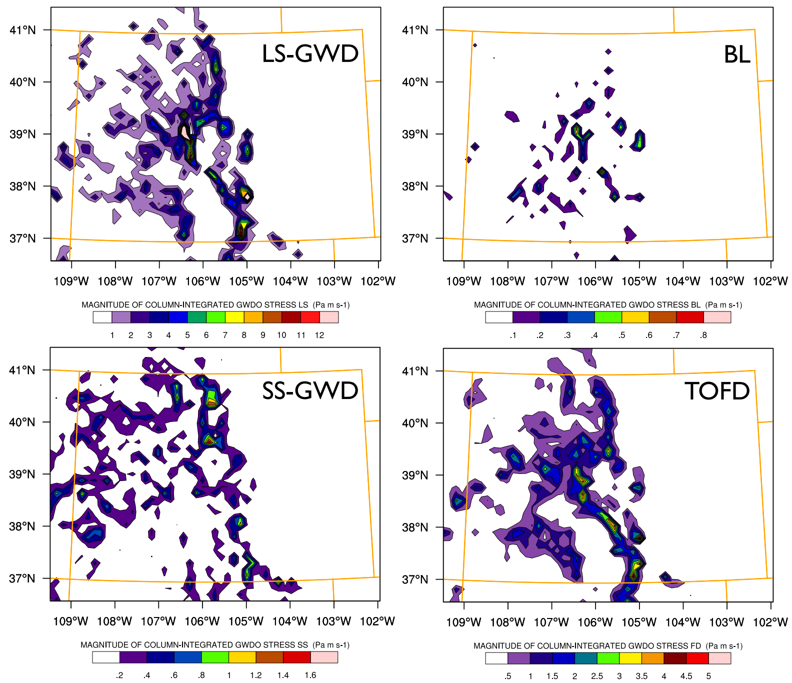


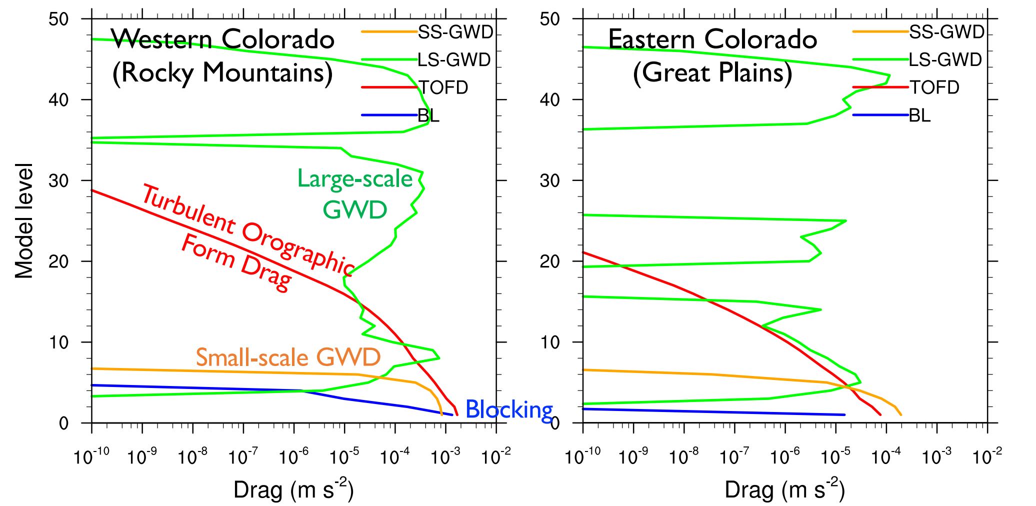
Momentum flux contributions from each orographic drag scheme

RAP (13km grid)

Surface stess (N m^{-2}) at 1400UTC 19 Sept. 2017
(zoomed-in on Colorado -- 7am local time)



Vertical profiles of area-averaged momentum tendencies due to drag at 1400UTC 19 Sept. 2017

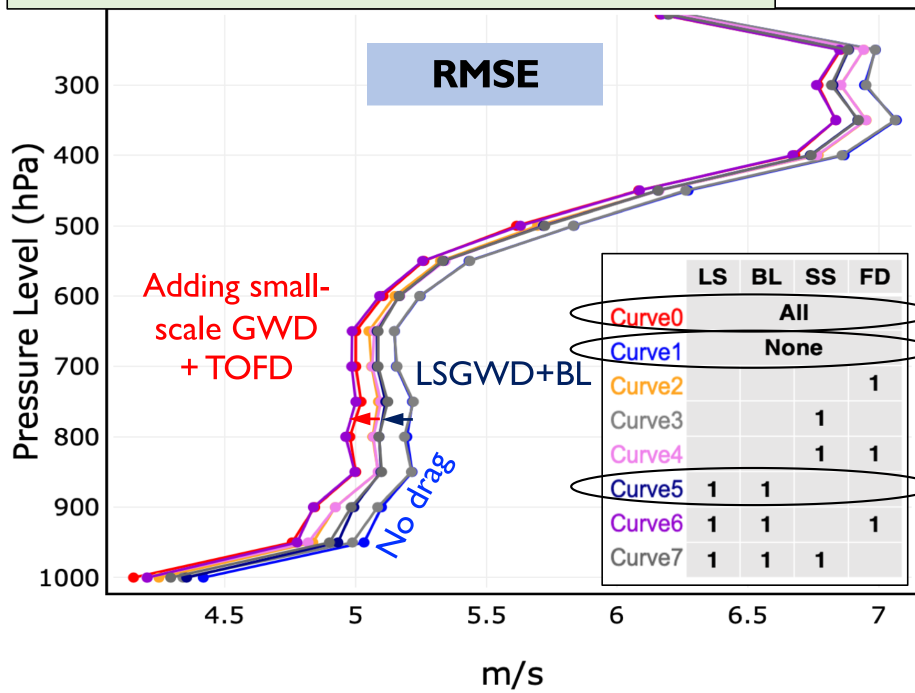


Impact of small-scale drag schemes in the RAP

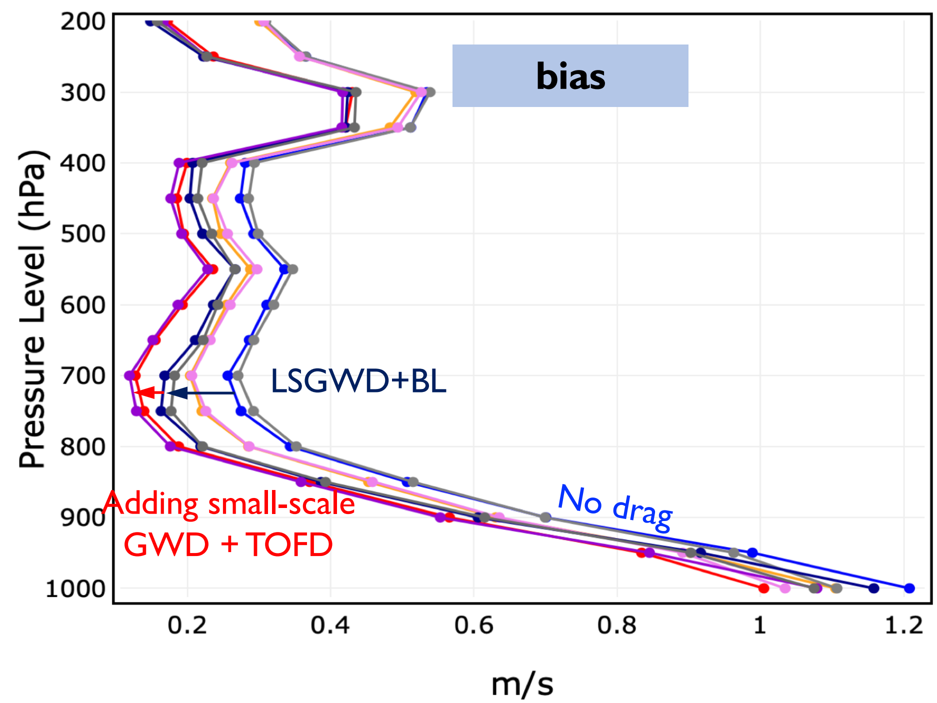
Reforecasts
2–15 Feb 2019

Note the benefits of SSGWD and TOFD

27-h wind: full RAP domain, 00/12 UTC



	LS	BL	SS	FD
Curve0	All			
Curve1	None			
Curve2				1
Curve3			1	
Curve4			1	1
Curve5	1	1		
Curve6	1	1		1
Curve7	1	1	1	



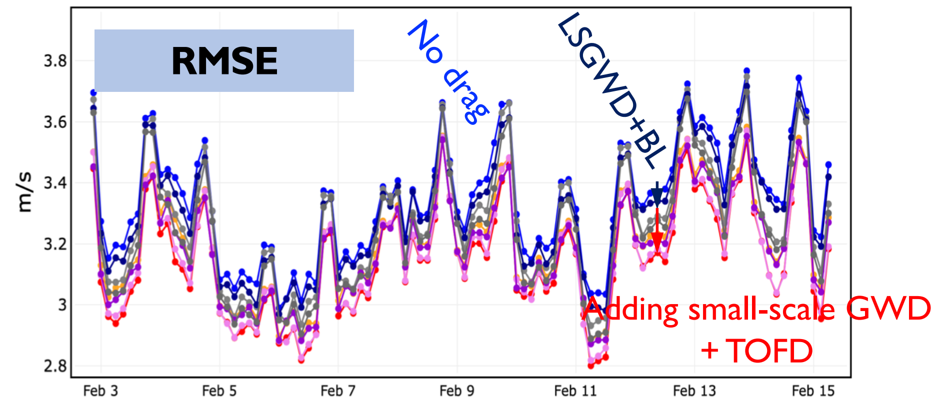
Plots courtesy of Jaymes Kenyon

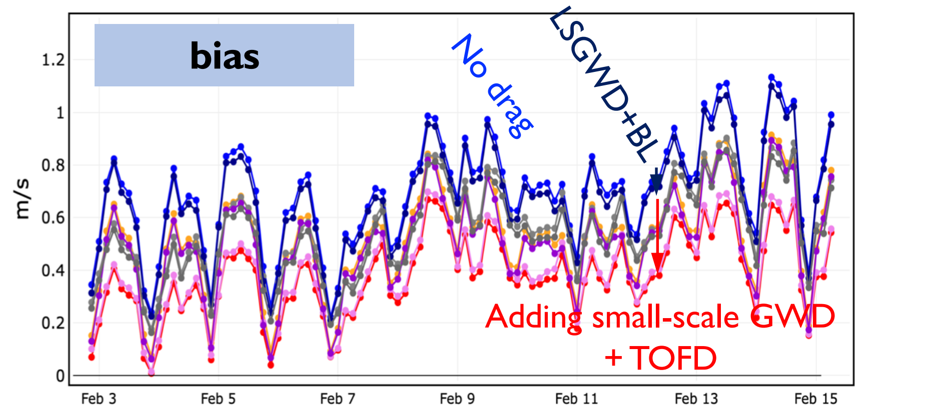
Impact of small-scale drag schemes in the RAP

Reforecasts
2–15 Feb 2019

21-h 10-m wind: full RAP domain

	LS	BL	SS	FD
Curve0	All			
Curve1	None			
Curve2				1
Curve3			1	
Curve4			1	1
Curve5	1	1		
Curve6	1	1		1
Curve7	1	1	1	





Plots courtesy of Jaymes Kenyon

Global FV3GFS pre-test results
C768 - 127 levels

					GSL Drag Suite			
Exp	ugwp version	Large-scale Orographic GWD	Blocking	Non-orographic	Large-scale orographic GWD	Blocking	Small-scale Orographic GWD	TOFD
GFSv16 Control Archives	0	Active	Active	Active	Inactive	Inactive	Inactive	Inactive
B0	0	Active	Active	Active	Inactive	Inactive	Inactive	Inactive
B1_bugfix	1	Active	Active	Active	Inactive	Inactive	Inactive	Inactive
B2_bugfix	1	Active	Active	Active	Inactive	Inactive	Active	Active
B3_bugfix	1	Inactive	Inactive	Active	Active	Active	Active	Active

UGWPv1 (B1_bugfix, B2_bugfix, B3_bugfix)

Active

Inactive

Seven 7-day forecasts in January 2020
Forecast length: 10 days for v0, 8 days for v1

Developmental Testbed Center

Slide courtesy of Ligia Bernardet, Weiwei Li, et. al (DTC Global T&E Team)

Testing Protocol for Pre-tests

- **Resolution:** C768L127
- **Initialization**: 7 forecasts in Jan 2020 (*01, 06, 11, 16, 21, 26, and 31;* 00 Z cycle)
- **Forecast length:** Target 10-day
  - But note only 8-day forecasts were conducted for the v1 runs
- **Control:** Experiment 0 - CCPP-based ~GFSv16

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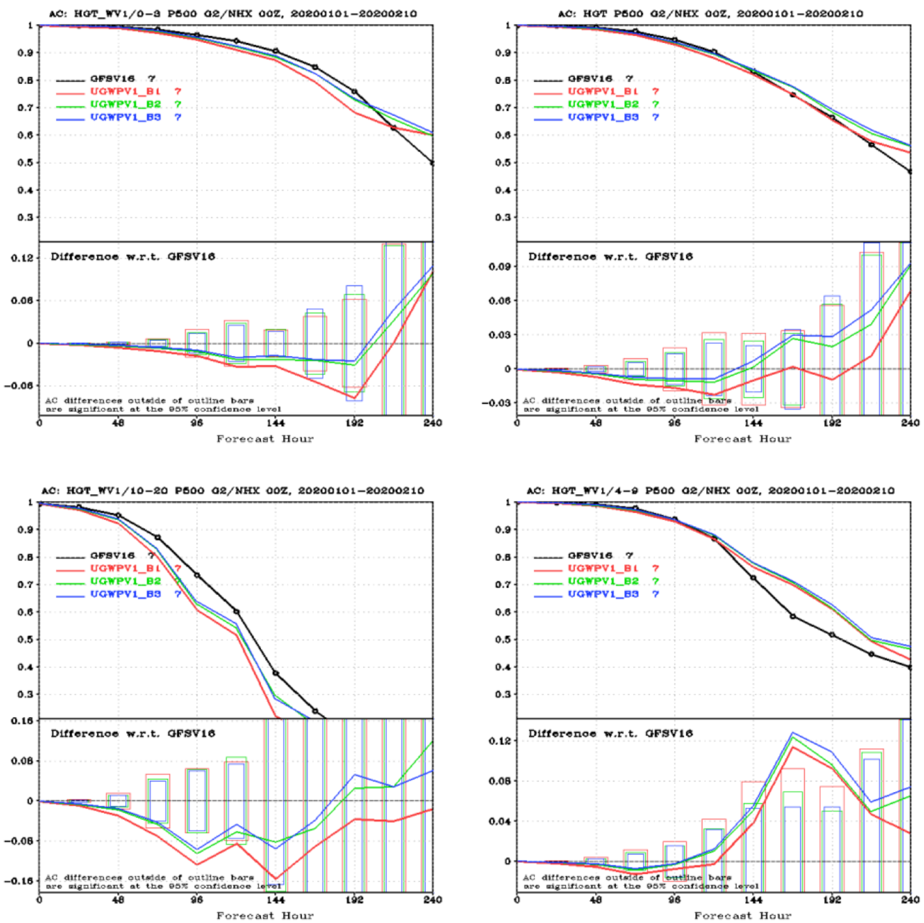
500 -hPa geop ACC (NHem)



UGWP v1 w/ bugfix

- Concerning lower 500 ACC for all three B* tests in first 5 days
- B1 (same configuration as control but with GWP v1 and newer code base) is worse than control
- B3 experiment outperforms the other two experiments and the GFSv16 esp. at longer lead times - mostly attributed to improved smaller waves (wavenumber > 4)

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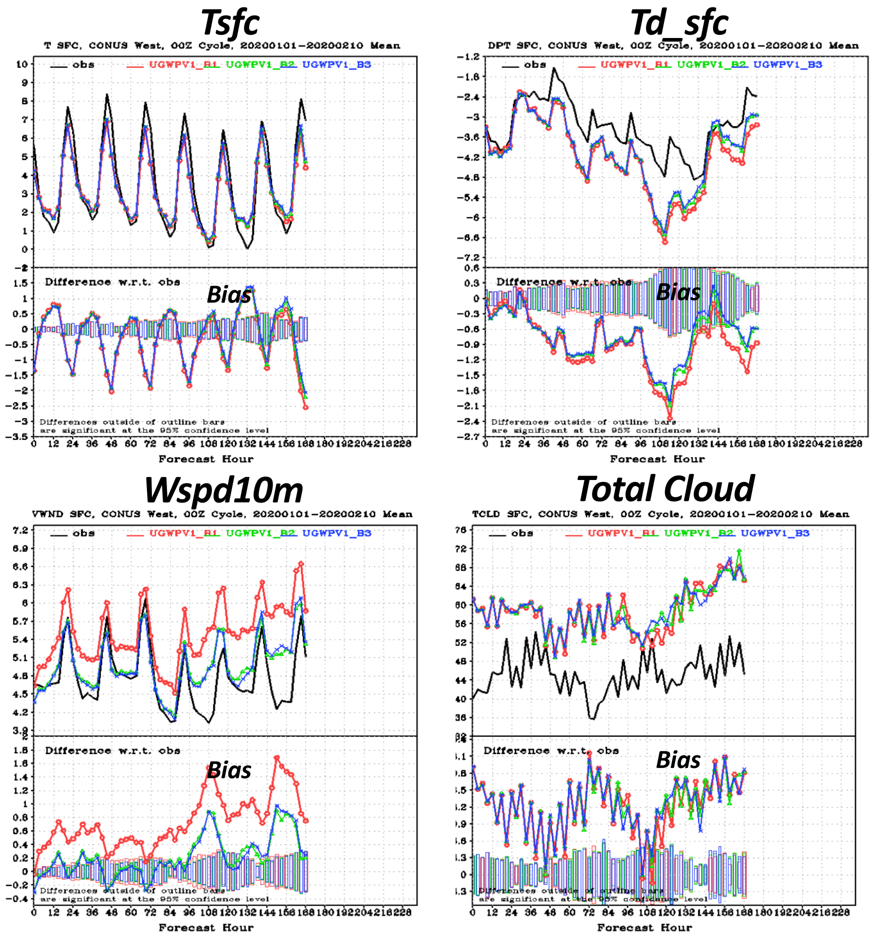
Surface parameters (T, Td, Wspd) & Total cloud cover: diurnal cycles and biases (**West CONUS; against sfc obs)**



UGWP v1 w/ bugfix

Temp

- bias not sensitive to GWD

Moisture

- All exp show near-surface dry bias
- B3 and B2 outperform B1 beyond Day 4

Winds

- Smaller (better) 10-m Wspd in B2 and B3 than B1

Total cloud cover

- bias not sensitive to GWD

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Future work: Representing 3D topography by Fourier series of 2D ridges

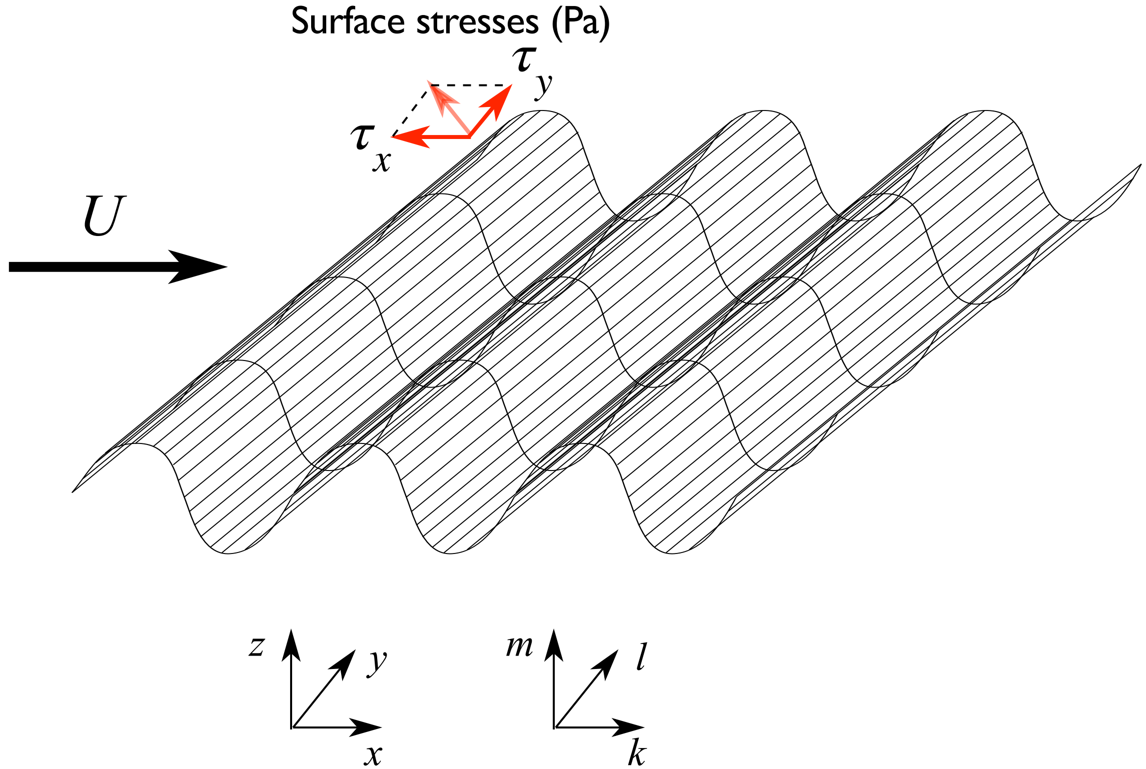
From linear theory:

$$\tau_x(k,l) = -\frac{1}{2}\rho_0 U^2 \sqrt{\frac{N^2}{U^2} - k^2}\,\frac{k^2}{\sqrt{k^2+l^2}}\left[H(k,l)\right]^2$$

$$\tau_y(k,l) = -\frac{1}{2}\rho_0 U^2 \sqrt{\frac{N^2}{U^2} - k^2}\,\frac{lk}{\sqrt{k^2+l^2}}\left[H(k,l)\right]^2$$

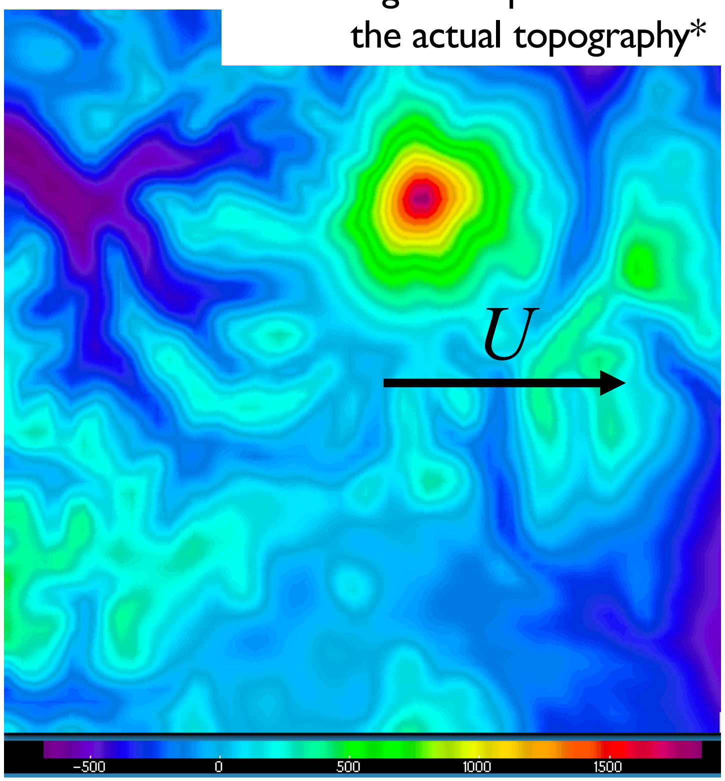
where,

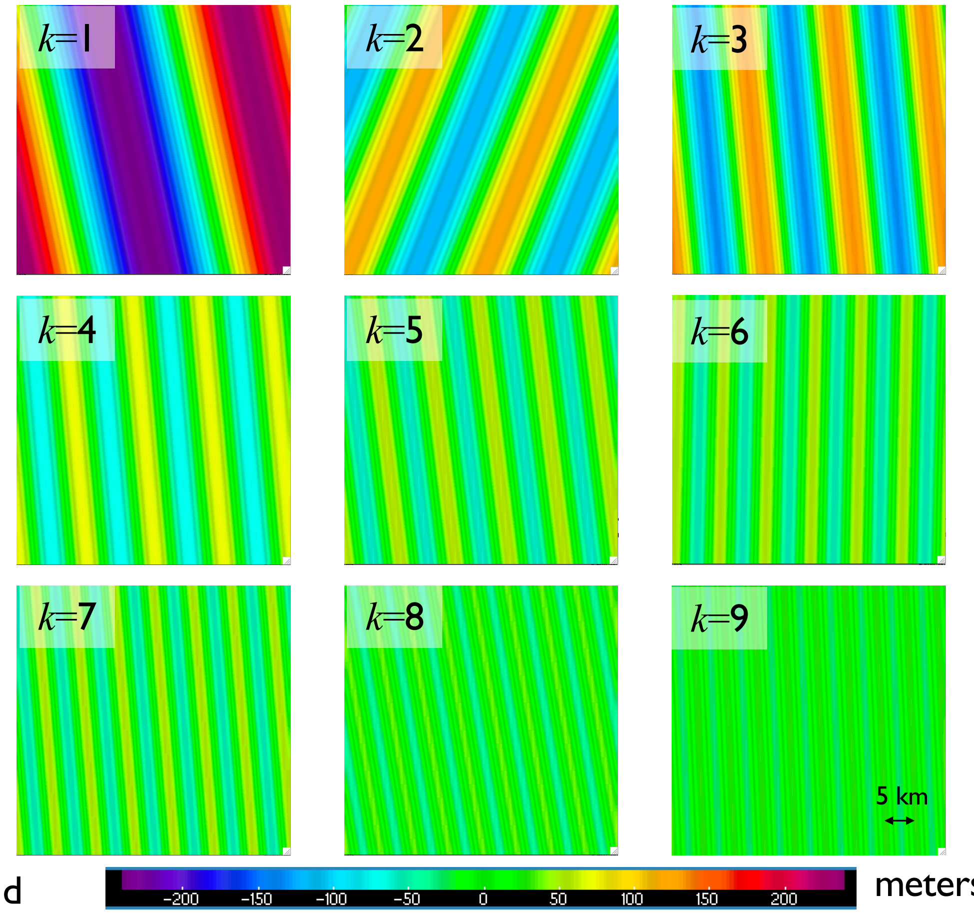
ρ_0 = air density (kg m^{-3})
N = Brunt-Väisälä frequency (s^{-1})
$H(k,l)$ = amplitude of mode (m)



Future work: Representing 3D topography by Fourier series of 2D ridges

The sum of the stresses of these nine ridges is equivalent to that of the actual topography*

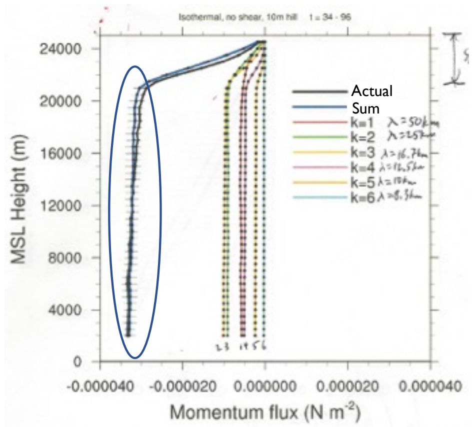




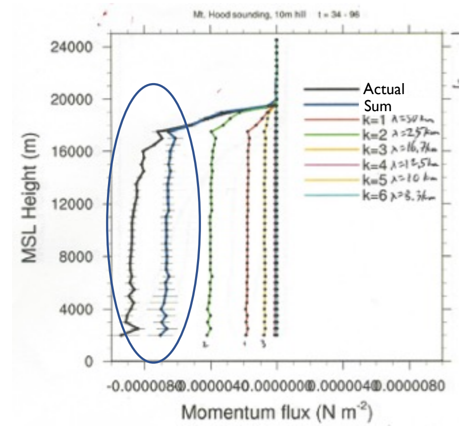
*If linear theory held

Proof of concept: High-resolution 2D model simulations over Gaussian hill (a GWD super-parameterization)

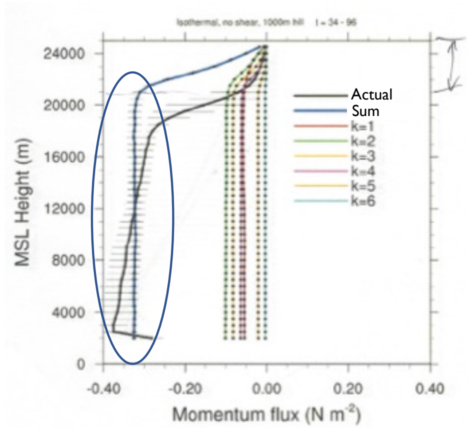
Isothermal, uniform *U*

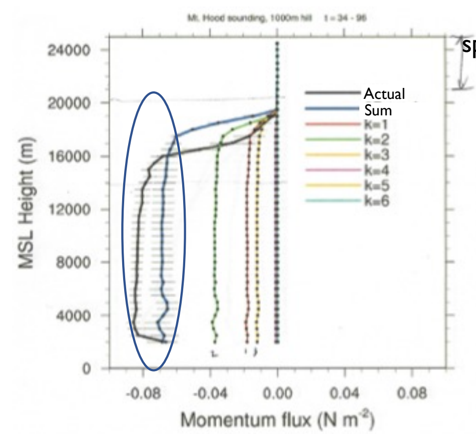


Realistic sounding



10 m hill
(linear)





sponge layer

1000 m hill
(nonlinear)

Summary

- The Unified Gravity Wave Physics package includes:
  - The "traditional" orographic gravity wave drag and low-level blocking schemes
  - Drag sources from smaller-scale (~1km) topographic variations
  - Non-stationary gravity wave drag
- It is currently being tested and tuned in the FV3GFS
- The small-scale orographic drag parameterizations appear to improve forecast skill
- The scheme is available in the CCPP library of physical parameterizations