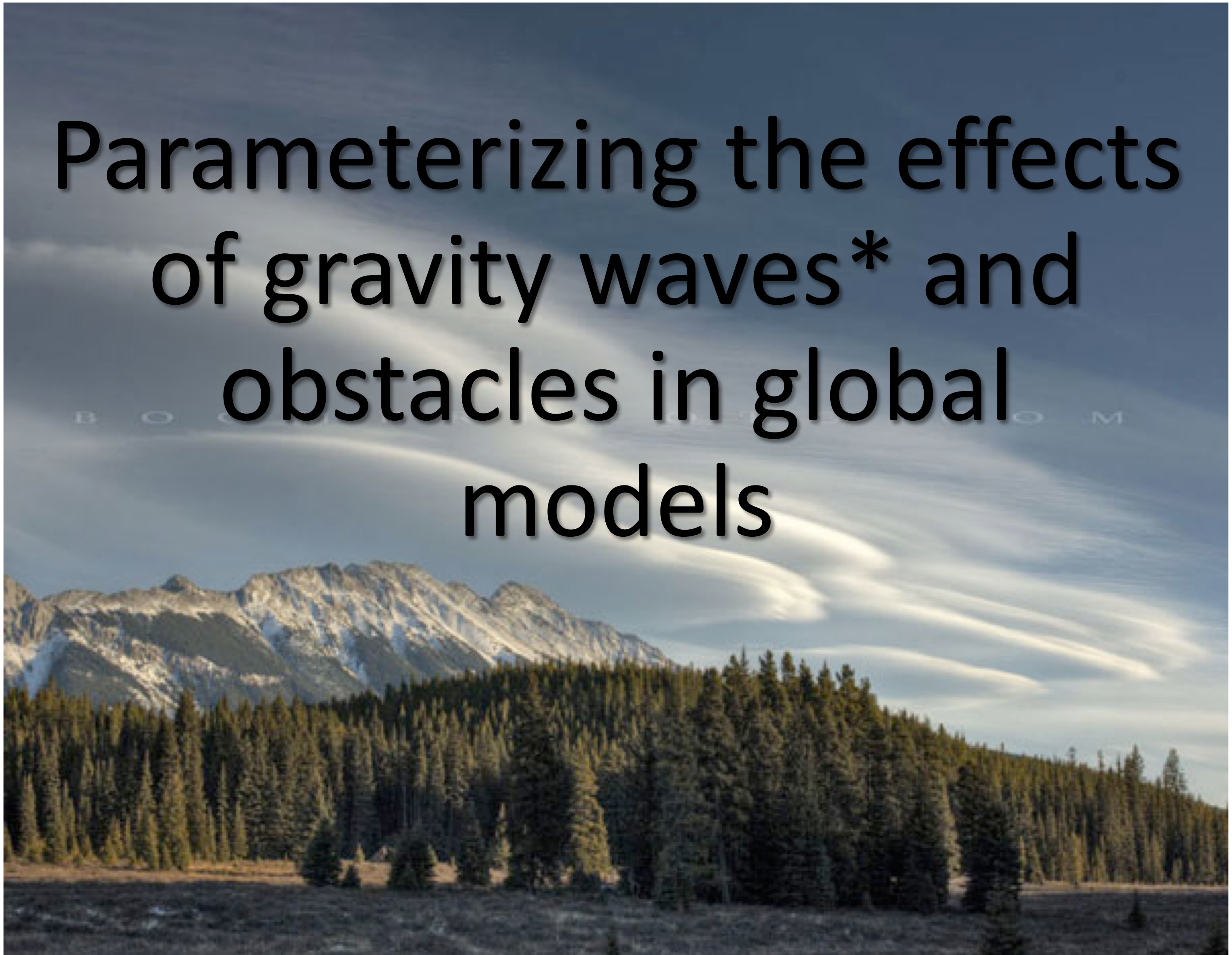
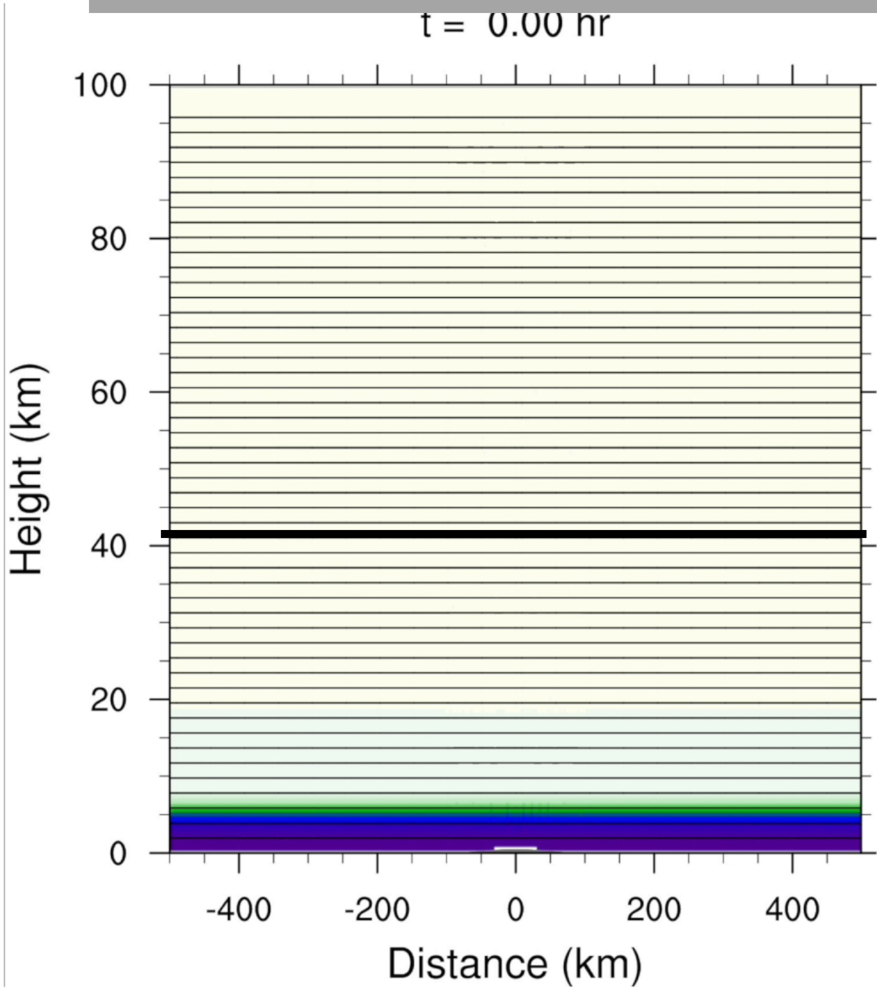
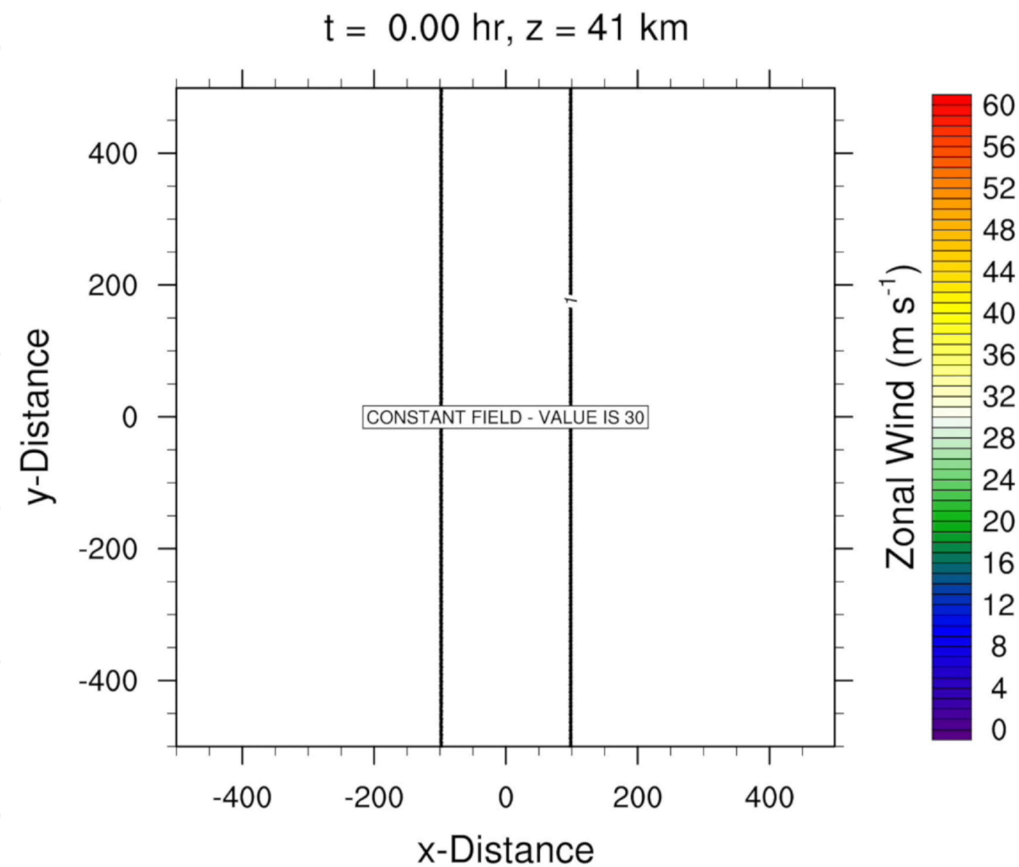
Parameterizing the effects of gravity waves* and obstacles in global models



*mostly “mountain waves”, i.e., gravity waves generated by mountains

Cross section through orographic gravity wave train





3-D WRF

Animation courtesy of Chris Kruse

"bumpy" 2D ridge in 3D flow

Outline

- History and impacts
- GW observations
- Basic structure of GW parameterization
- Future directions

Gravity wave impacts

This talk will emphasize orographic effects, but in high-top models parameterized non-orographic gravity waves must be included as well. Key impacts:

- Drive Quasi-Biennial Oscillation (QBO) in equatorial zonal (E-W) winds
- Close-off mesopause winter jets and drive zonal mean mesopause temperature reversal (summer ***very cold ~120K)***

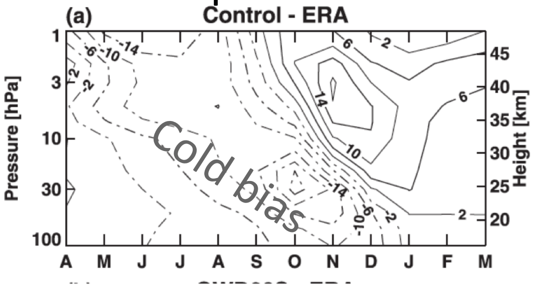
Gravity wave impacts

C. Hines, R. Lindzen 1970;'s 80's: Demonstrate that GW drag has o(1) role in climate of mesosphere

Palmer et al. 1986, McFarlane 1987, Miller et al. 1989: OGW drag has positive effects on NWP and climate model performance

Lott &Miller 1997, Scinocca&McFarlane 2000, Webster et al 2003 … Sandu et al 2017 , : OGW form drag/blocking has *further* positive effects on forecast skill and climate skill

SH Temp Bias 70S-90S



McLandress et al. 2012: SH Cold bias in CMAM reduced by artificial increase in GW drag. Note, this bias has impact for ozone chemistry.

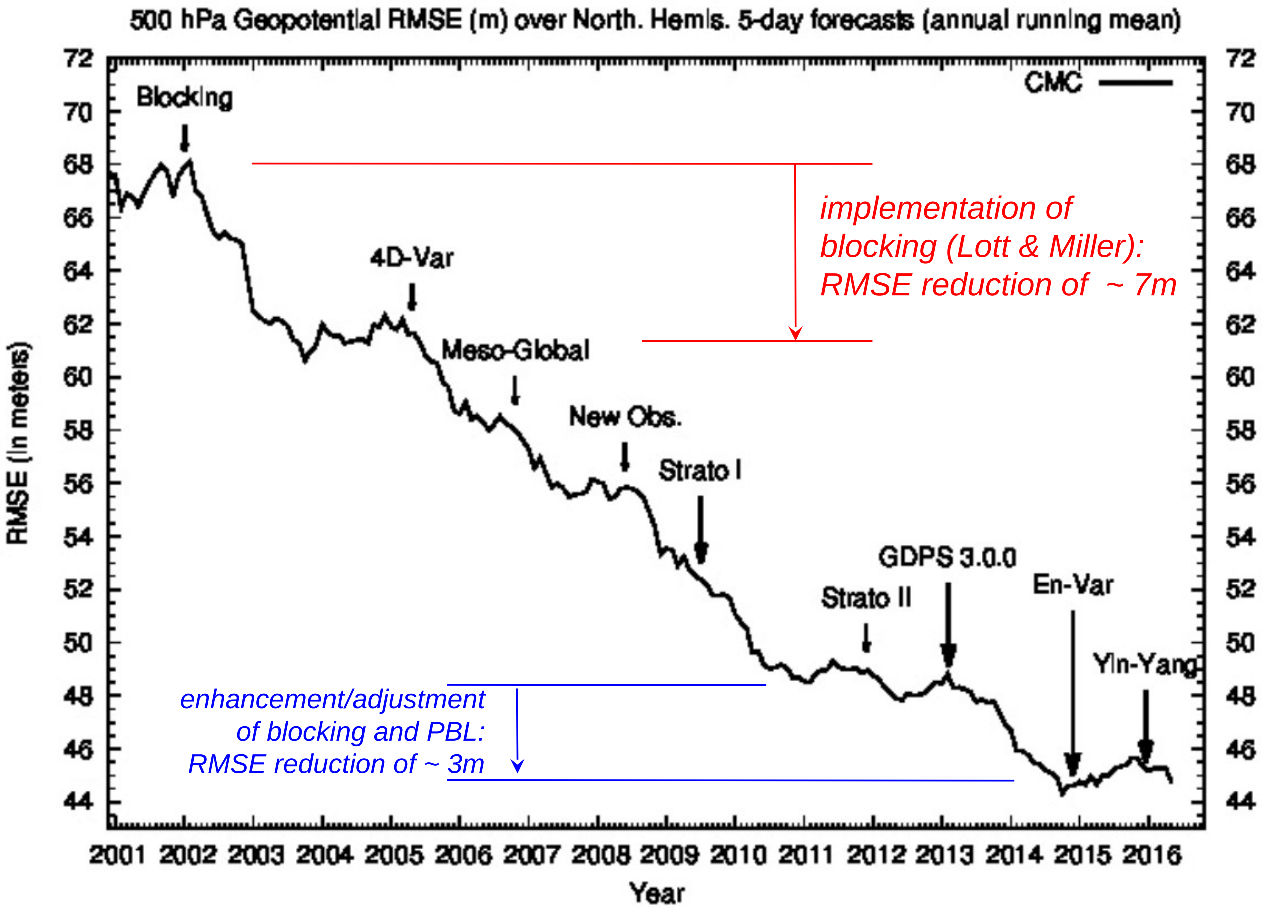
Pithan et al. 2016: OGW drag impacts blocking (large-scale) statistics

van Niekerk et al. 2017: OGW drag modulates climate change signals in simulations

Non-dynamical impacts: Polar stratospheric cloud (PSC) formation (Carslaw et al 1997) Greenland precipitation and mass balance, cirrus clouds (?), chemistry(?)

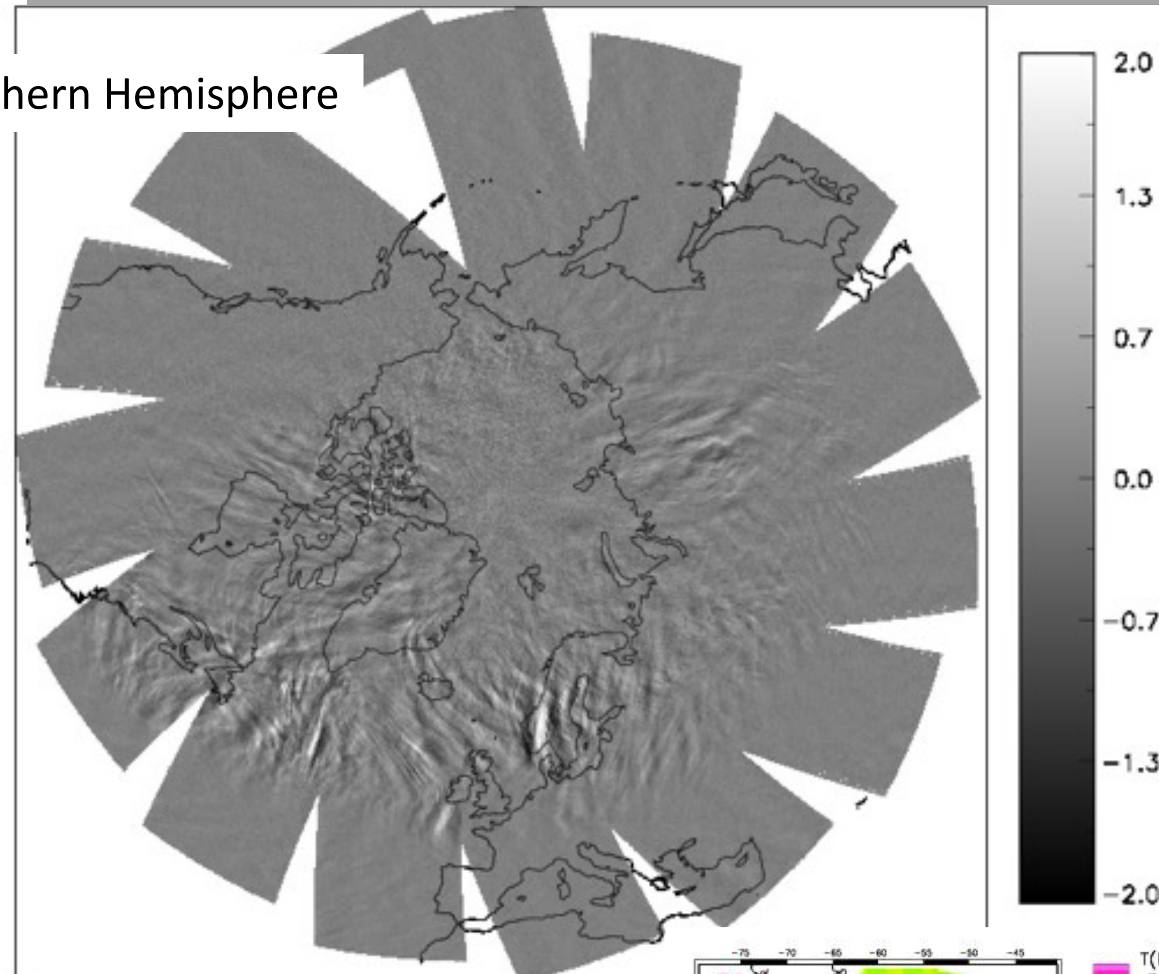
Motivation for WGNE Drag Project:
importance/impact of parametrization of orographic processes

Example: Impact of orographic blocking in the Canadian global model



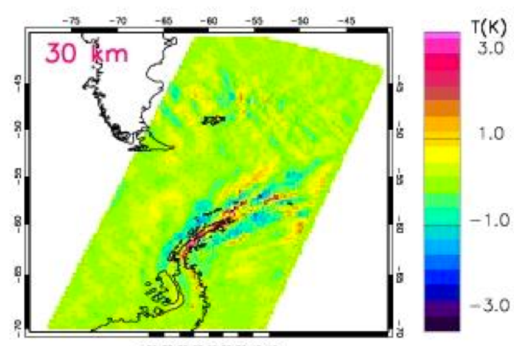
Amospheric Infrared Sounder (AIRS) observations of mountain waves in the stratosphere altitude 30-40km *(Joan Alexander)*

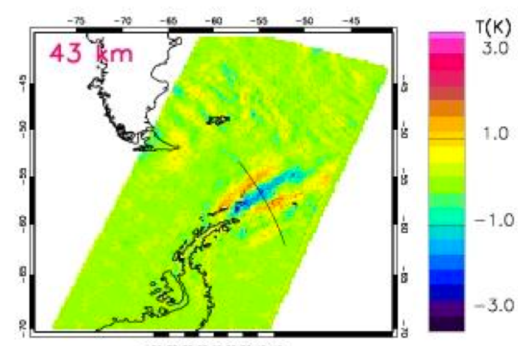
Northern Hemisphere



Recent work with satellite and super-pressure balloon obs suggests the existence of gravity wave “hotspots” in the stratosphere: Southern Andes/Antarctic Pen, Norway, S Greenland. Few extreme events contribute lots of mean drag.

Southern Hemisphere





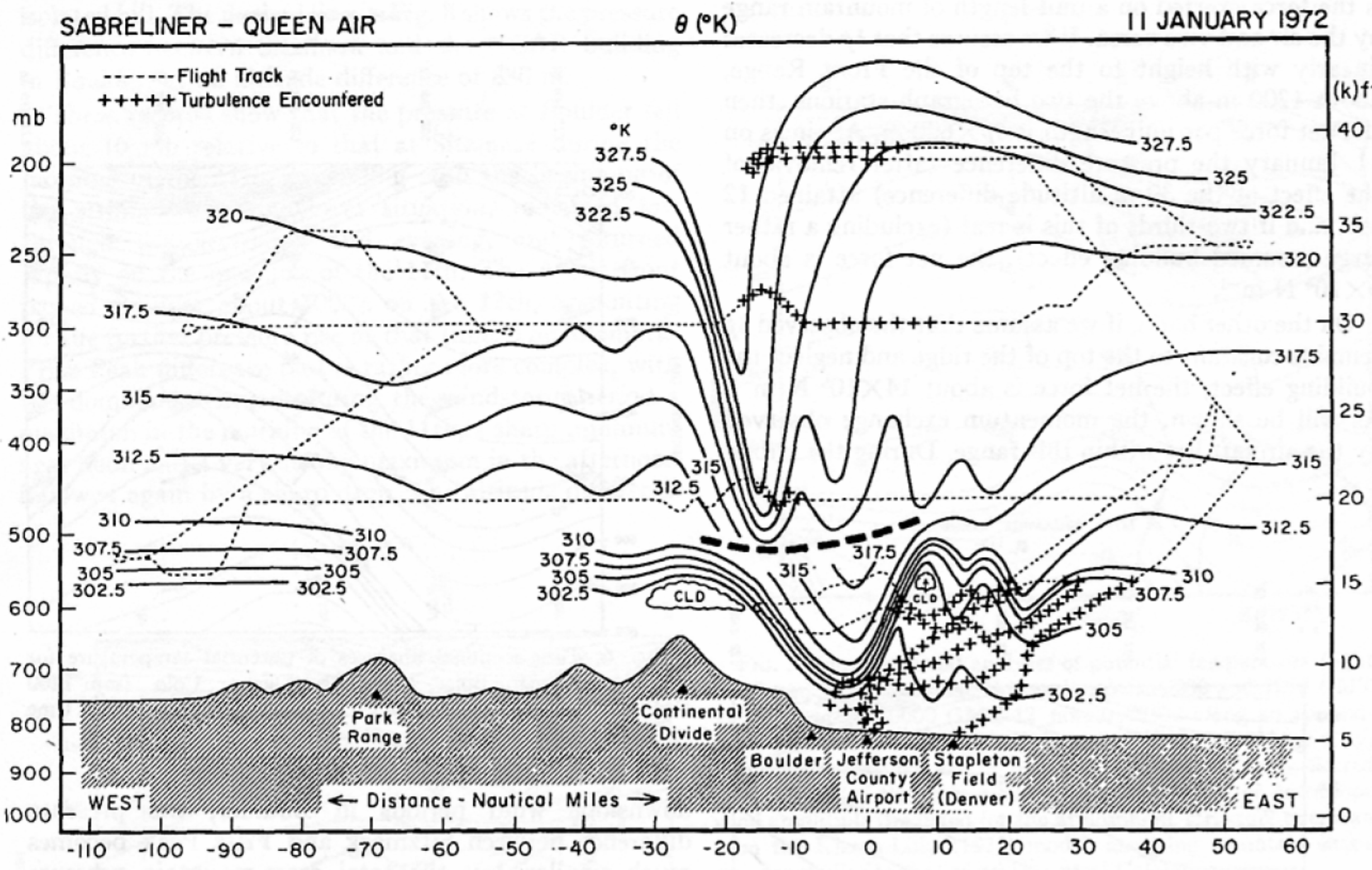
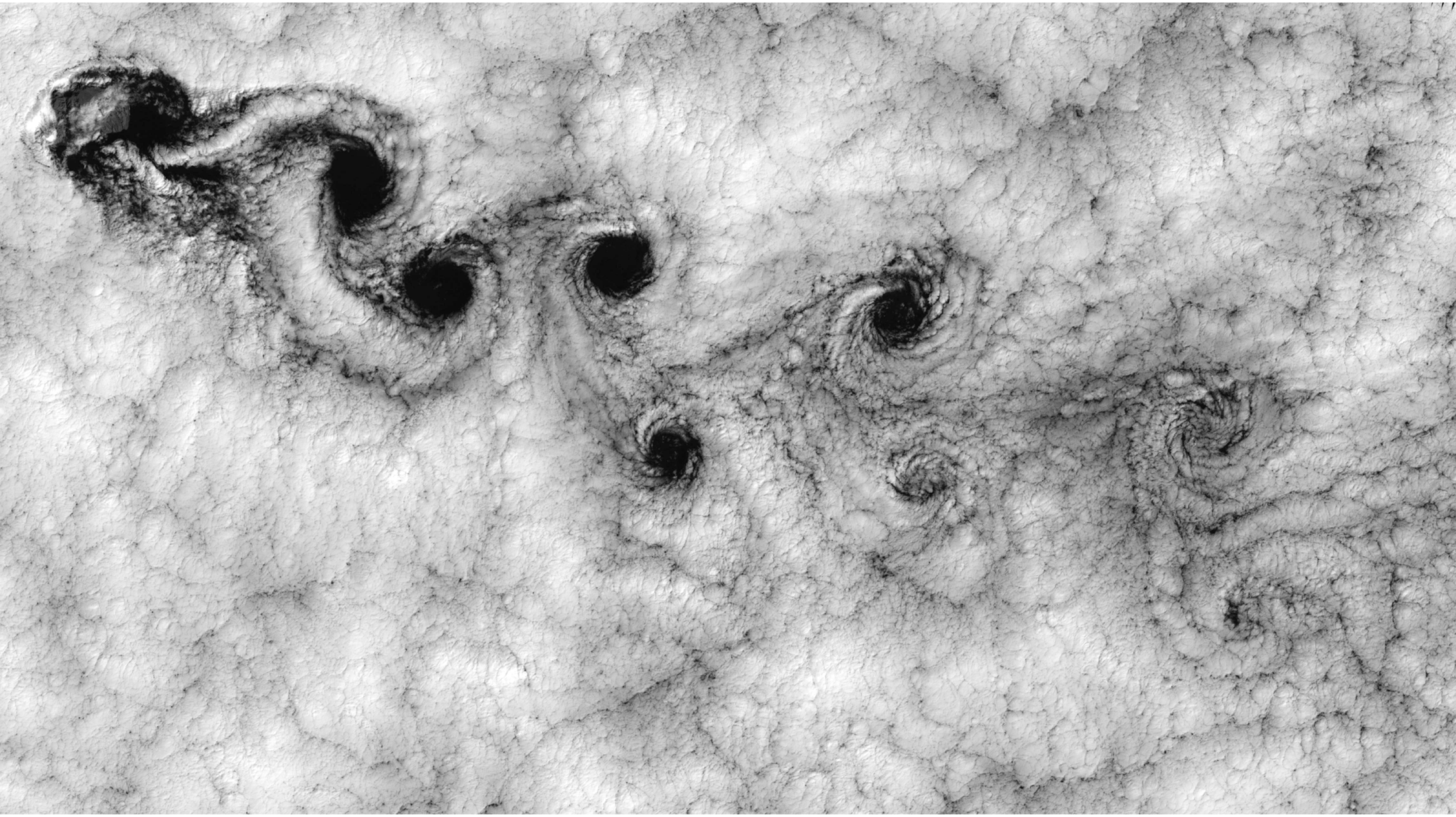
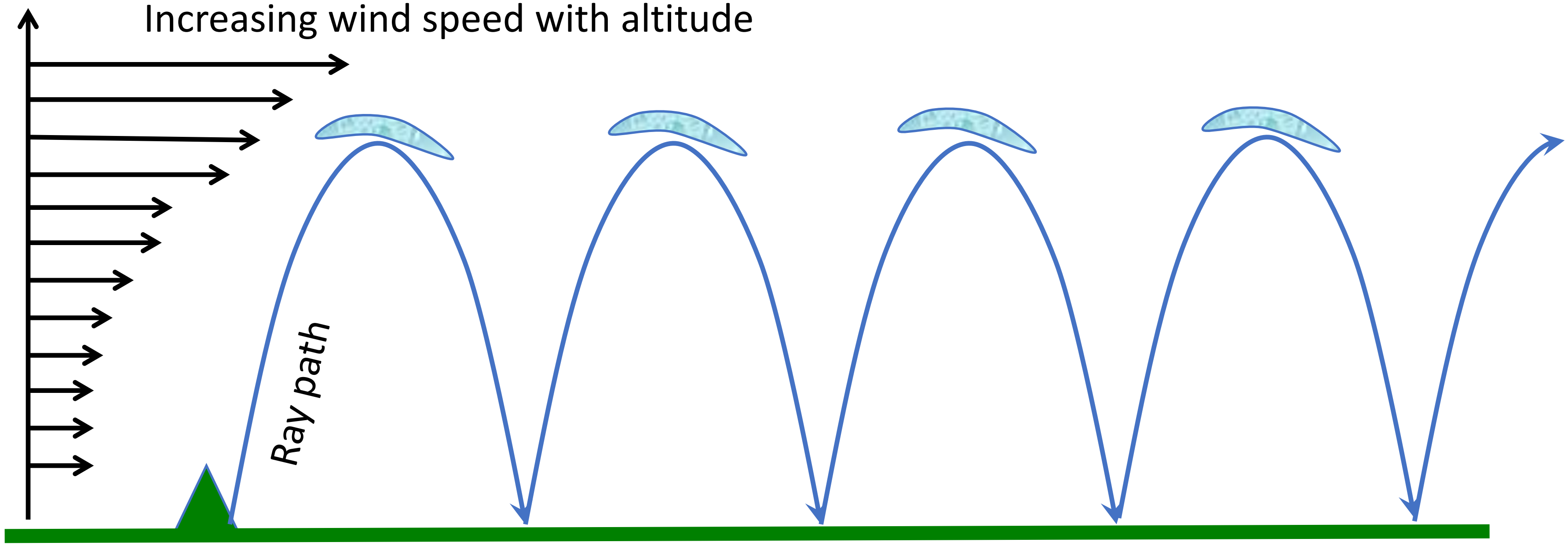


FIG. 7. Analysis of the potential temperature field (solid lines) from aircraft flight data and sondes taken on 11 January 1972. The dashed lines show aircraft track, with periods of significant turbulence shown by pluses. The heavy dashed line separates data taken by the Queen Air at lower levels before 2200 GMT from that taken by the Sabreliner in the middle and upper troposphere after 0000 GMT (12 January). The aircraft flight tracks were made along an approximate 130°–310° azimuth, but the distances shown are along the east-west projection of those tracks.


Boeing B-52H 'Stratofortress'
©USAF Museum Photo Archives

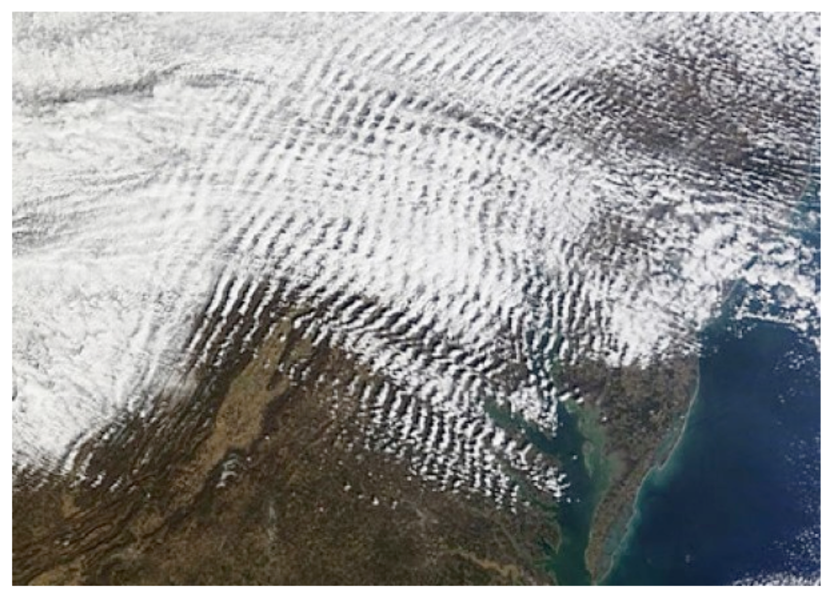


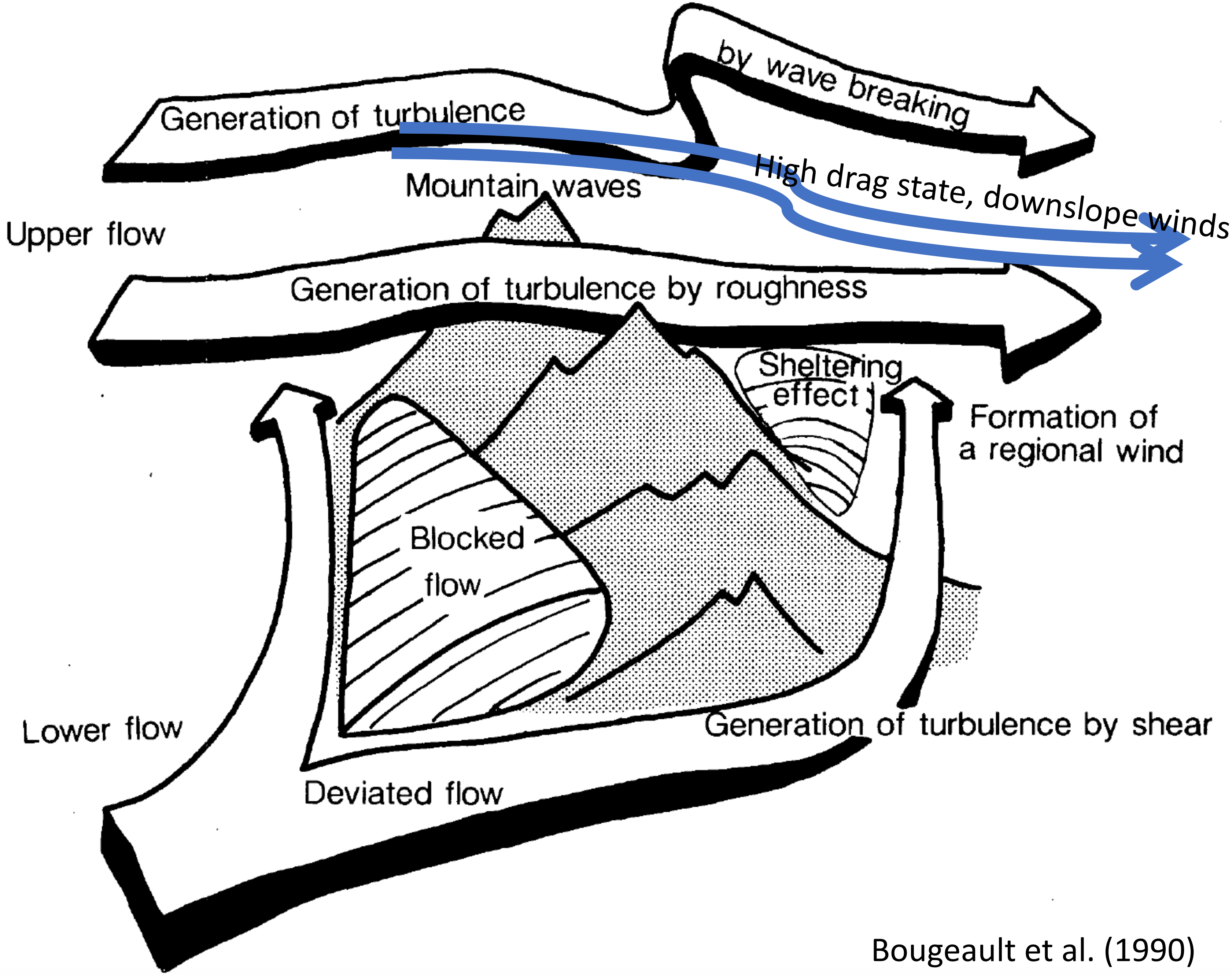


Trapped lee waves. Vertical wavenumber m given by

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

Waves turn where m^2 becomes <0



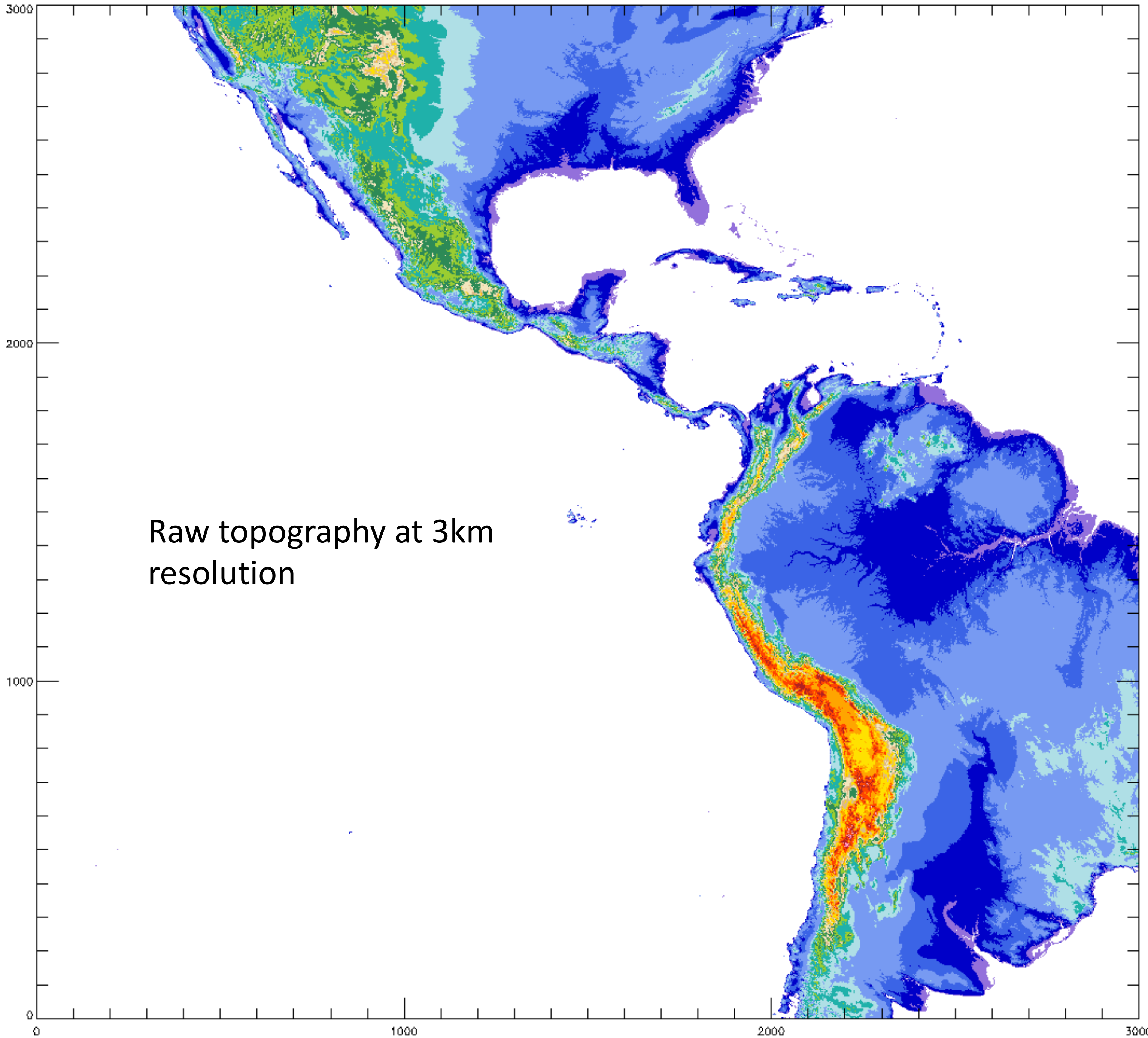


Bougeault et al. (1990)

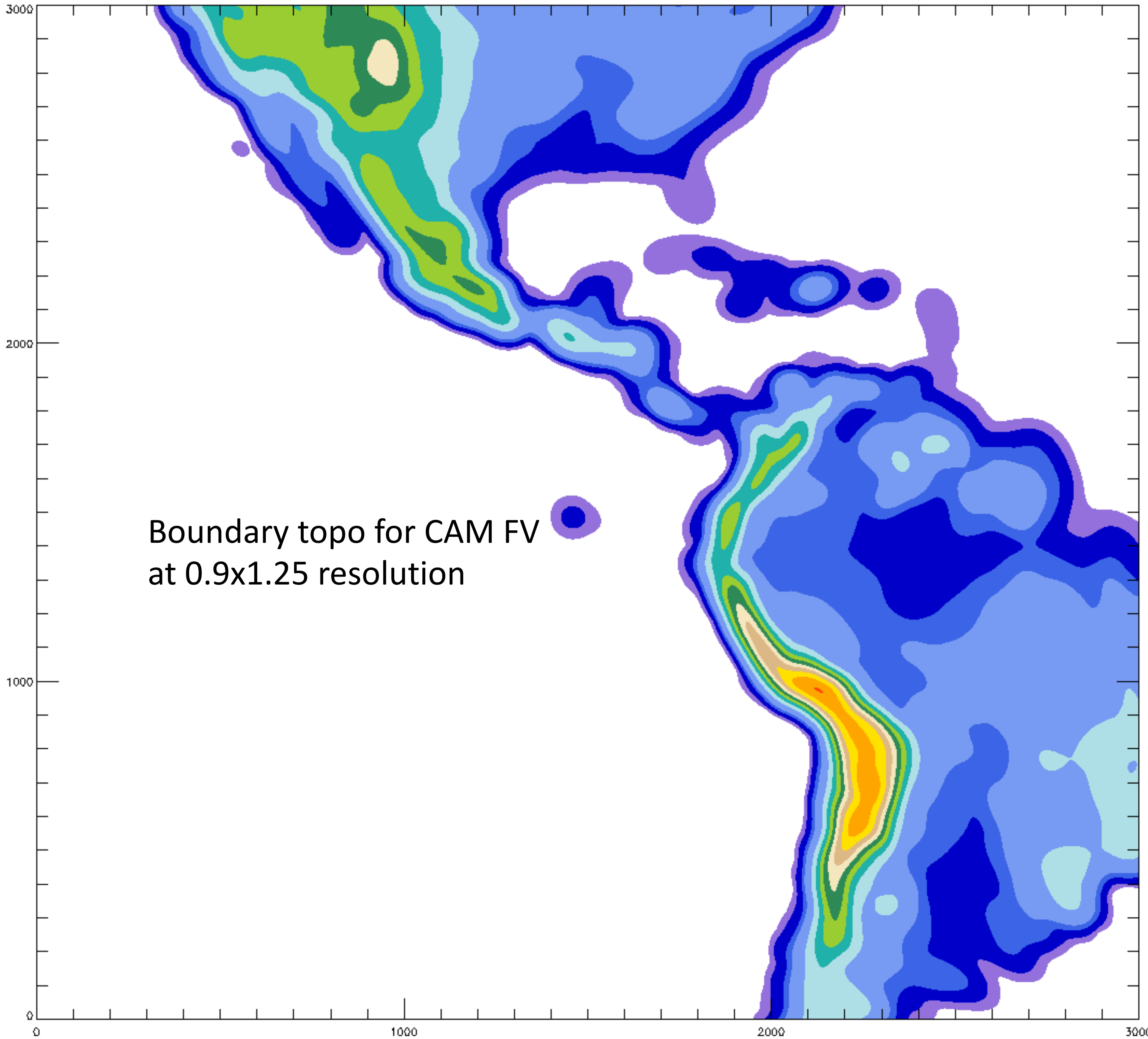
FIG. 2. A schematic of the flow around and over the Pyrénées (see subhead a in section 3).

How do we parameterize GW/orographic effects in a global model?

I) Forcing
II) Propagation and dissipation



Raw topography at 3km resolution


Boundary topo for CAM FV
at 0.9x1.25 resolution
3000
2000
1000
0
0
1000
2000
3000

How does subgrid orography affect atmospheric momentum ?

Turbulent, small-scale, … (obstacles <5km)

- PBL Form drag

Waves

- Mesoscale blocking and low-level nonlinearities
- Vertically propagating ***gravity waves***

Gravity wave basics

Stratification: Gravity waves need stable stratification

$$N^2 = \frac{g}{\Theta}\frac{\partial\Theta}{\partial z}$$

where, Θ is basic state potential temperature

- Note, if $\partial_z\Theta < 0$, warm air lies below cooler air and *N* is imaginary ➔convective instability
- Typical free-tropo strato values of *N* are 0.01 s^{-1} to 0.02 s^{-1} so buoyancy period ($2\pi/N$) is 300-600s

Gravity wave basics

Amplitude/nonlinearity: A basic length scale in gravity wave/stratified flow analysis

$$L = \frac{\bar{U}}{N}$$

where, $\bar{U}$ is mean horizontal wind. If $\bar{U}$~10m/s then *L*~500-1000m

For mountain heights $h \sim \frac{\bar{U}}{N}$ nonlinearities, blocking, high-drag states become important

For horizontal wavelength $\sim 2\pi\frac{\bar{U}}{N}$ (3km-6km) nonhydrostatic effects and wave trapping become important *(usual argument for separation into PBL and wave-based schemes)*

Subgrid momentum fluxes

Momentum Equation

$$\partial_t \rho \mathbf{u} + \ldots + \partial_z \rho w \mathbf{u} = -\nabla p - \rho \nabla \phi + \mathbf{F} + \ldots, \quad \rho \text{ is atmospheric density}$$

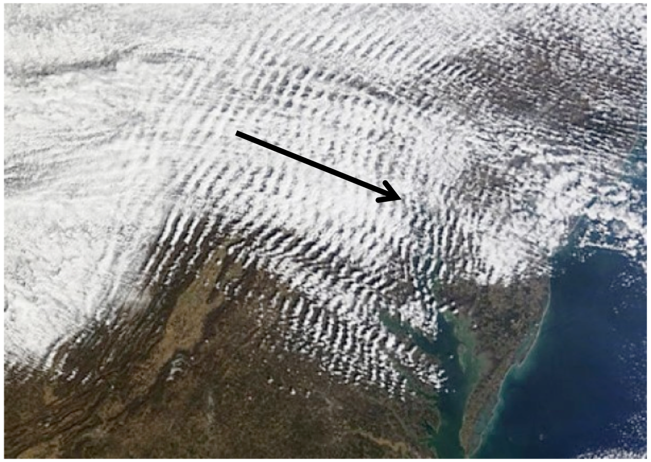
Grid box average momentum equation

$$\partial_t \bar{\rho} \bar{\mathbf{u}} + \ldots + \partial_z \bar{\rho} \bar{w} \bar{\mathbf{u}} = -\nabla \bar{p} - \bar{\rho} \nabla \bar{\phi} - \partial_z \overline{\rho u' w'}\, \mathbf{i} - \partial_z \overline{\rho v' w'}\, \mathbf{j} + \bar{\mathbf{F}}$$

Vertical derivatives of zonal and meridional subgrid vertical momentum fluxes produce drag forces

Subgrid momentum fluxes

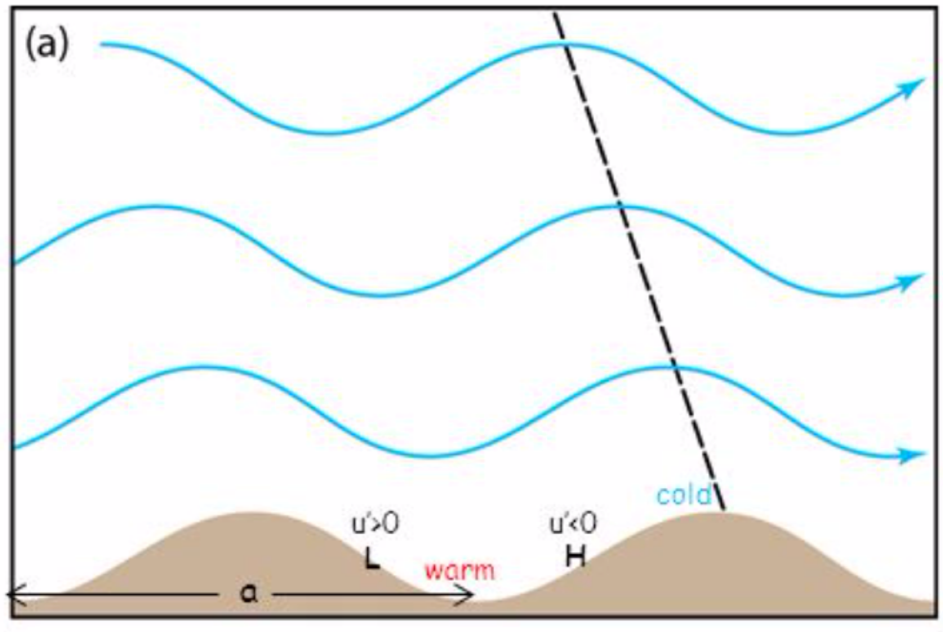
Let's turn into coordinates where "x" is perpendicular to wave crests



Our job is then to calculate

$$\tau = \overline{\rho u' w'}$$

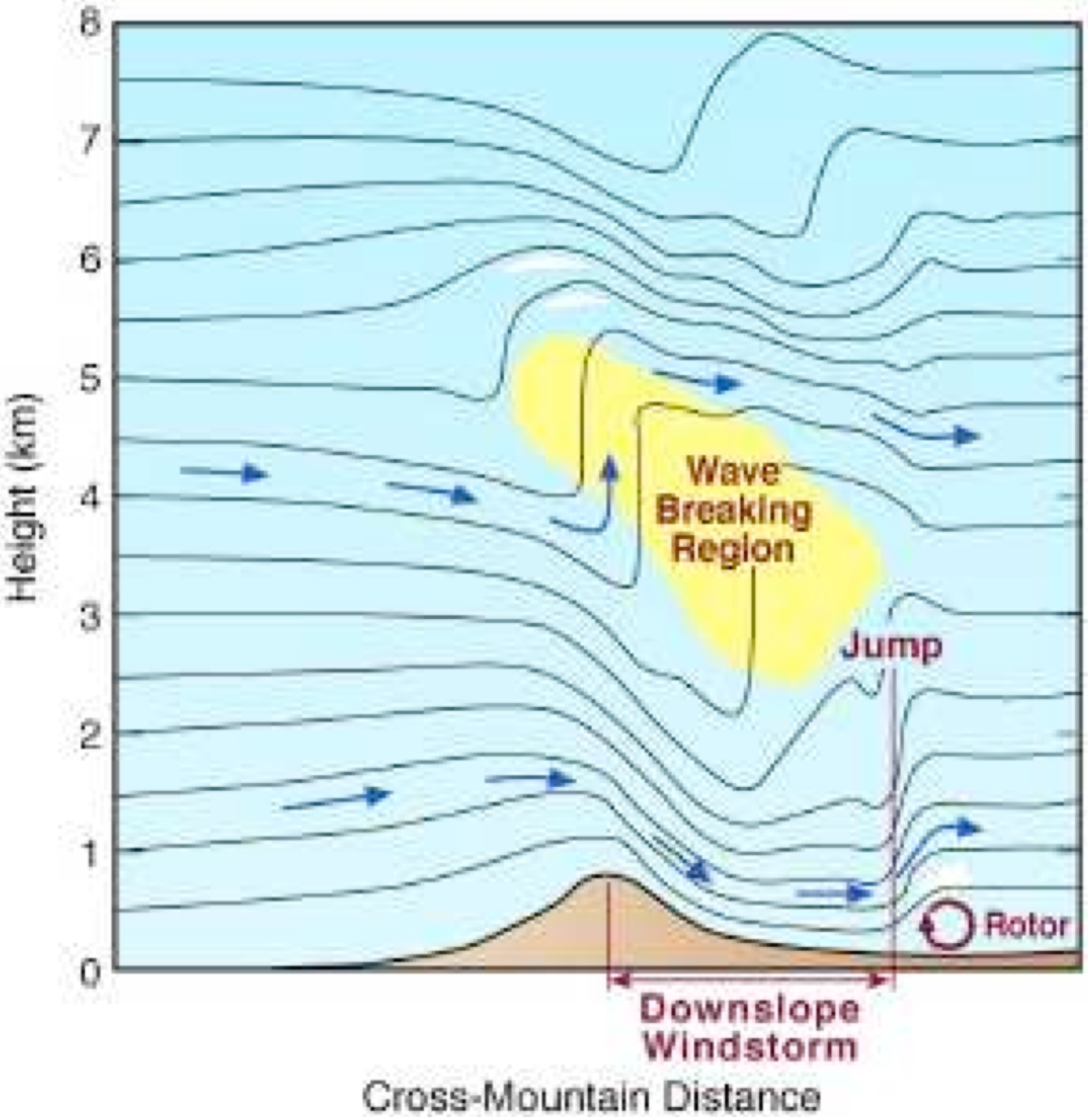
Subgrid momentum fluxes

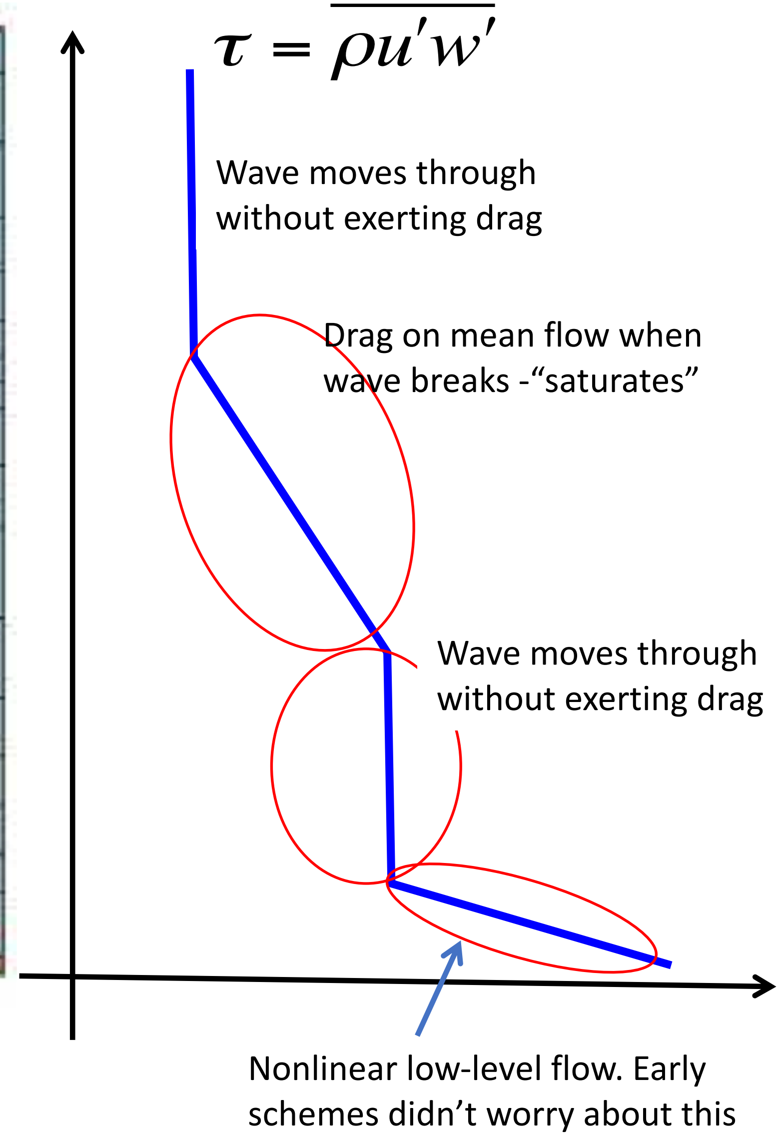


The underlying "cartoon" for gravity wave parameterization: 2D, WKB hydrostatic monochromatic wave (i.e., single mode).

Gives relatively simple relationships between *u',w' T' etc.*

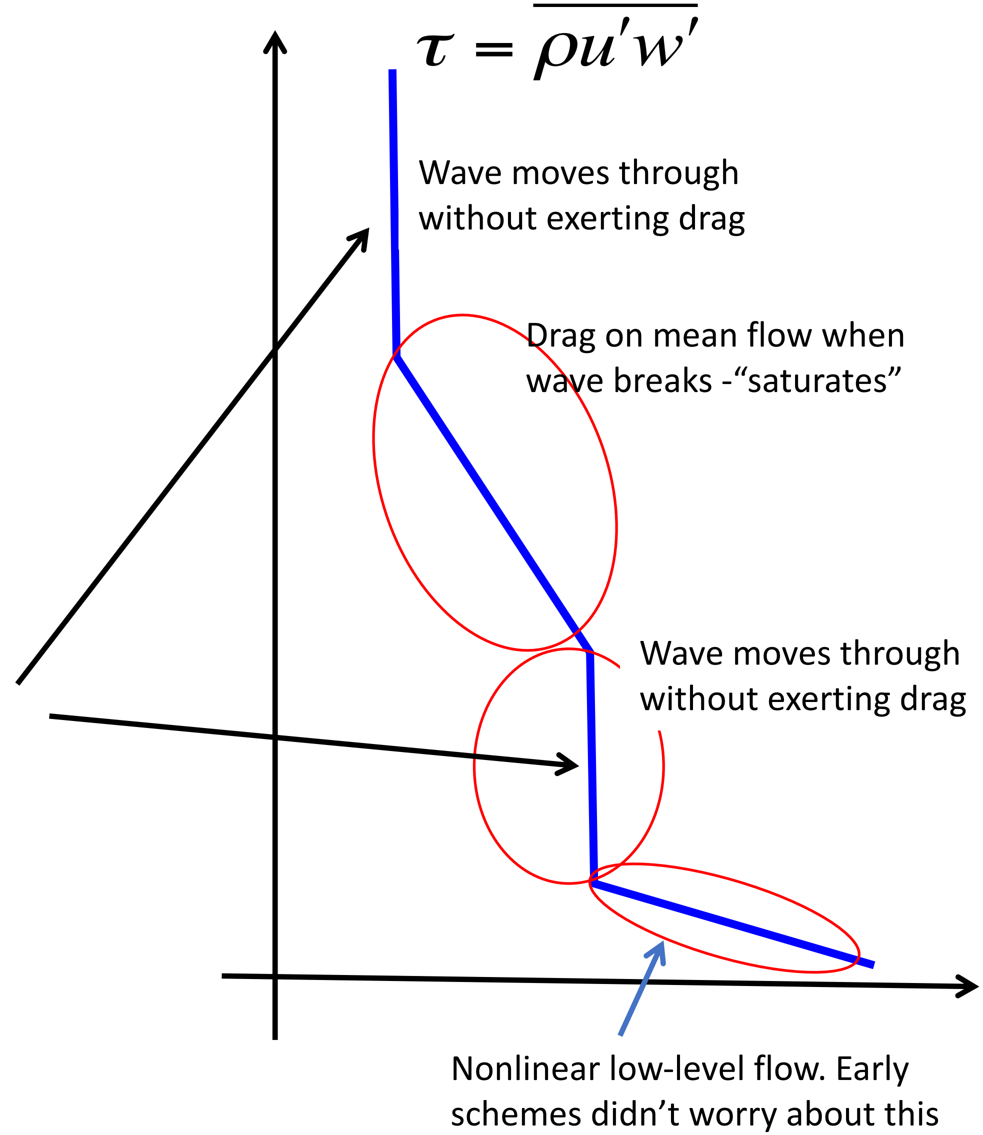
$$\tau = \overline{\rho u' w'}$$





Complex wave pattern ***<u>conceptualized as 2D monochromatic wave</u>*** controlled by "saturation"

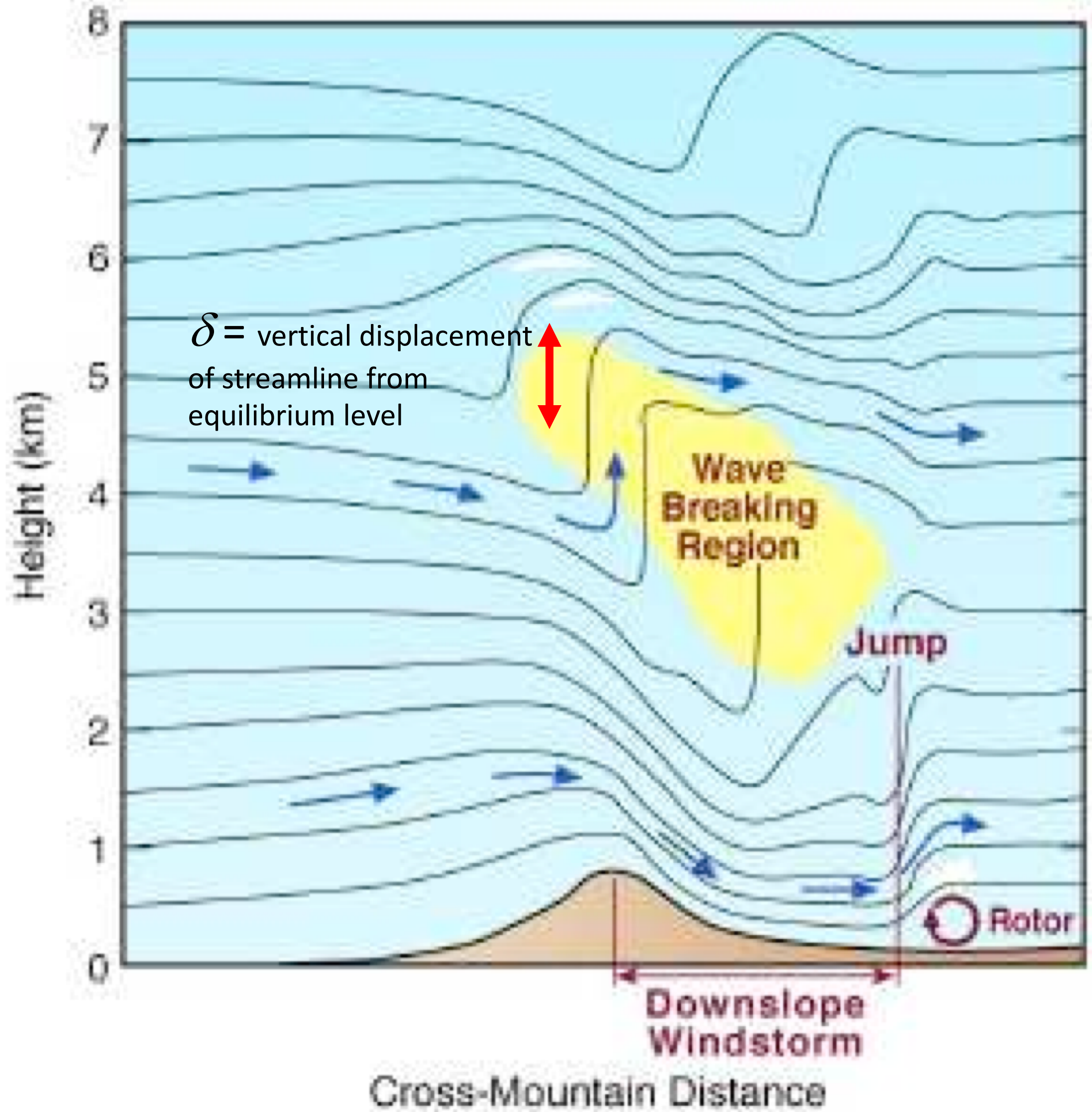
Lindzen, R. S. (1981). Turbulence and stress owing to gravity wave and tidal breakdown. *Journal of Geophysical Research*, *86*(C10), 9707-9714.

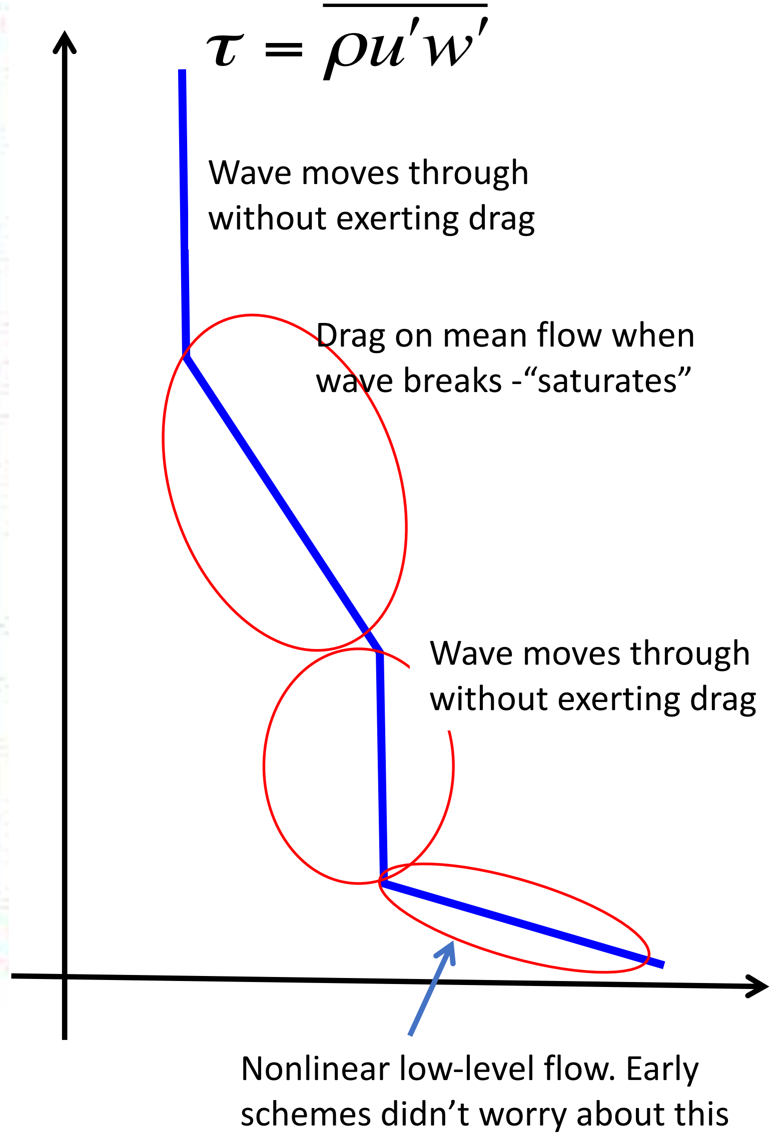


Eliassen-Palm theorem:
Non-dissipating waves conserve τ as they propagate vertically

Complex wave pattern conceptualized as 2D monochromatic wave controlled by “saturation”

Lindzen, R. S. (1981). Turbulence and stress owing to gravity wave and tidal breakdown. *Journal of Geophysical Research*, *86*(C10), 9707-9714.





How do we calculate τ based on topographic information?

Orographic gravity wave momentum flux based on δ and 2D hydrostatic gravity wave dispersion relationships

$$u' = N\delta$$

$$w' = k\bar{U}\delta$$

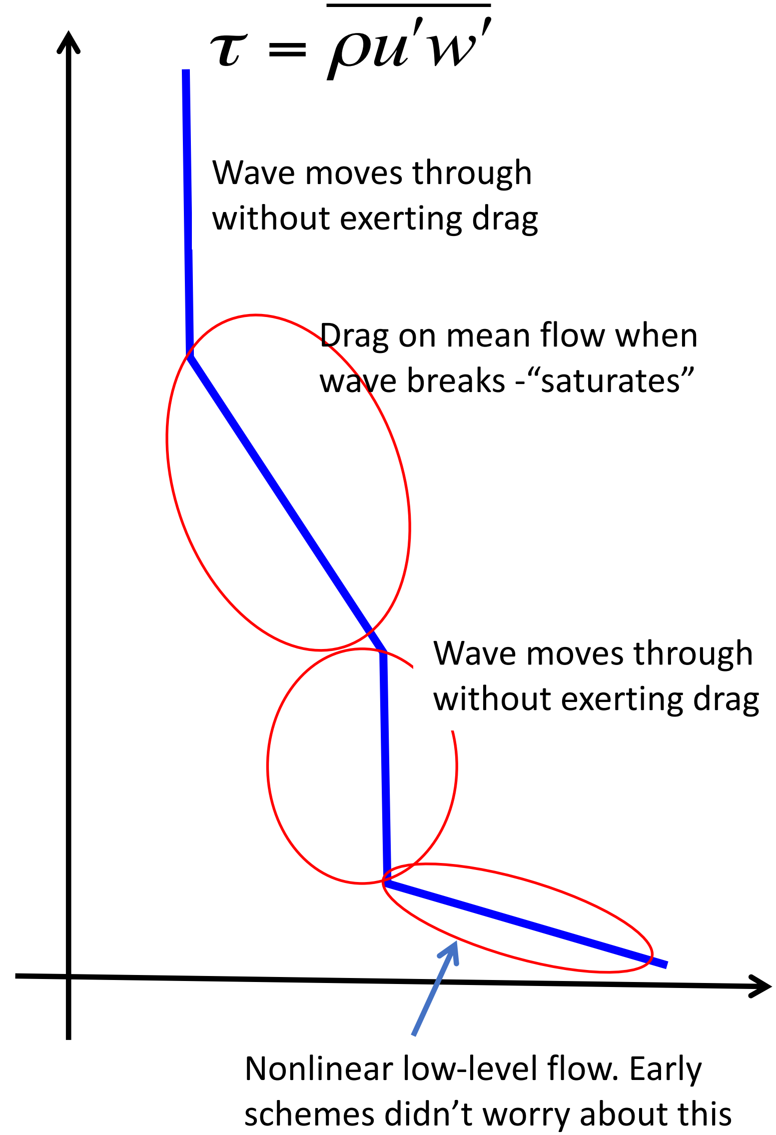
so momentum flux becomes

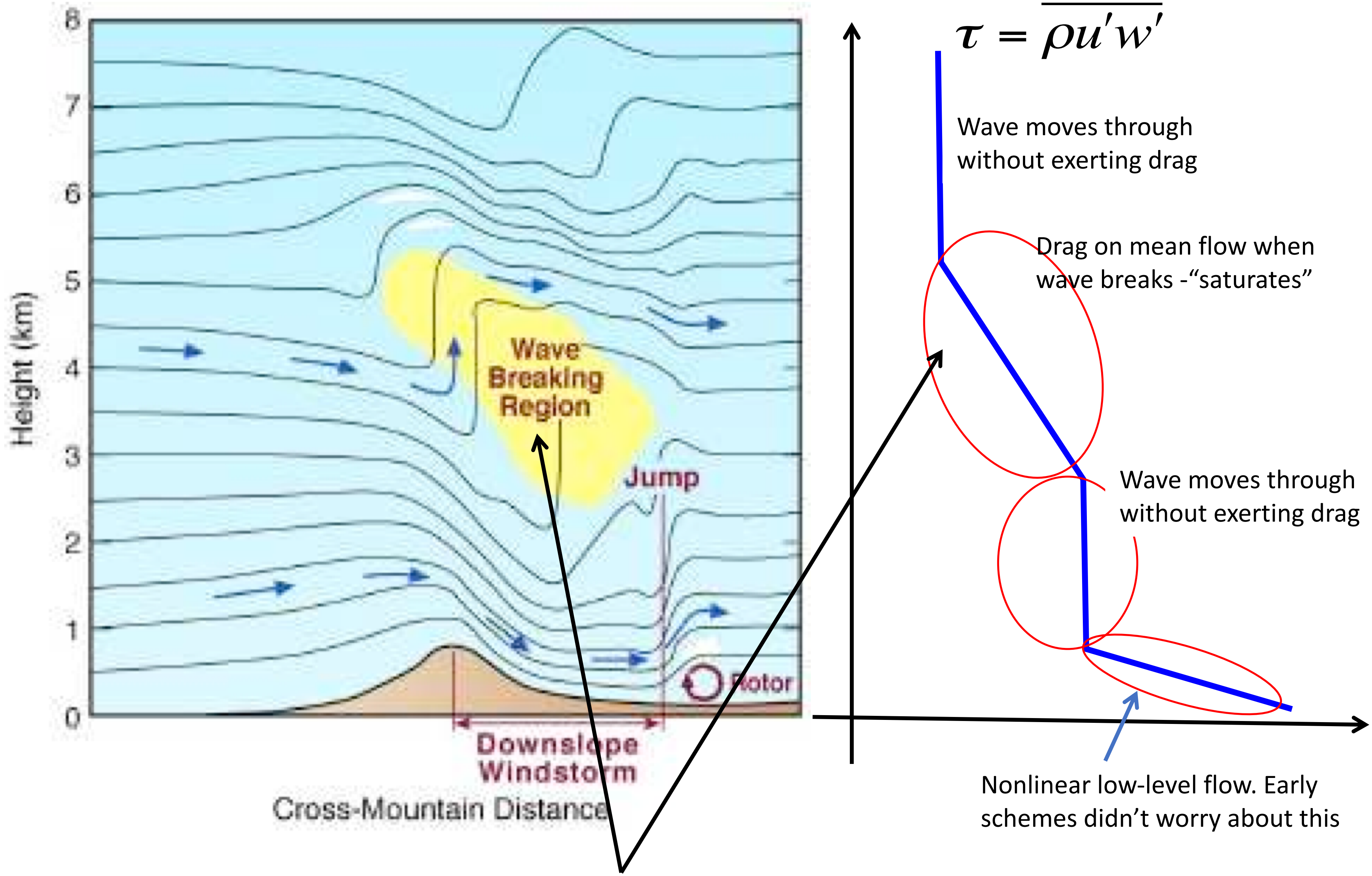
$$\tau \approx C\rho k\bar{U}N\delta^2$$

Intuitively obvious that δ at source level is related to mountain heights

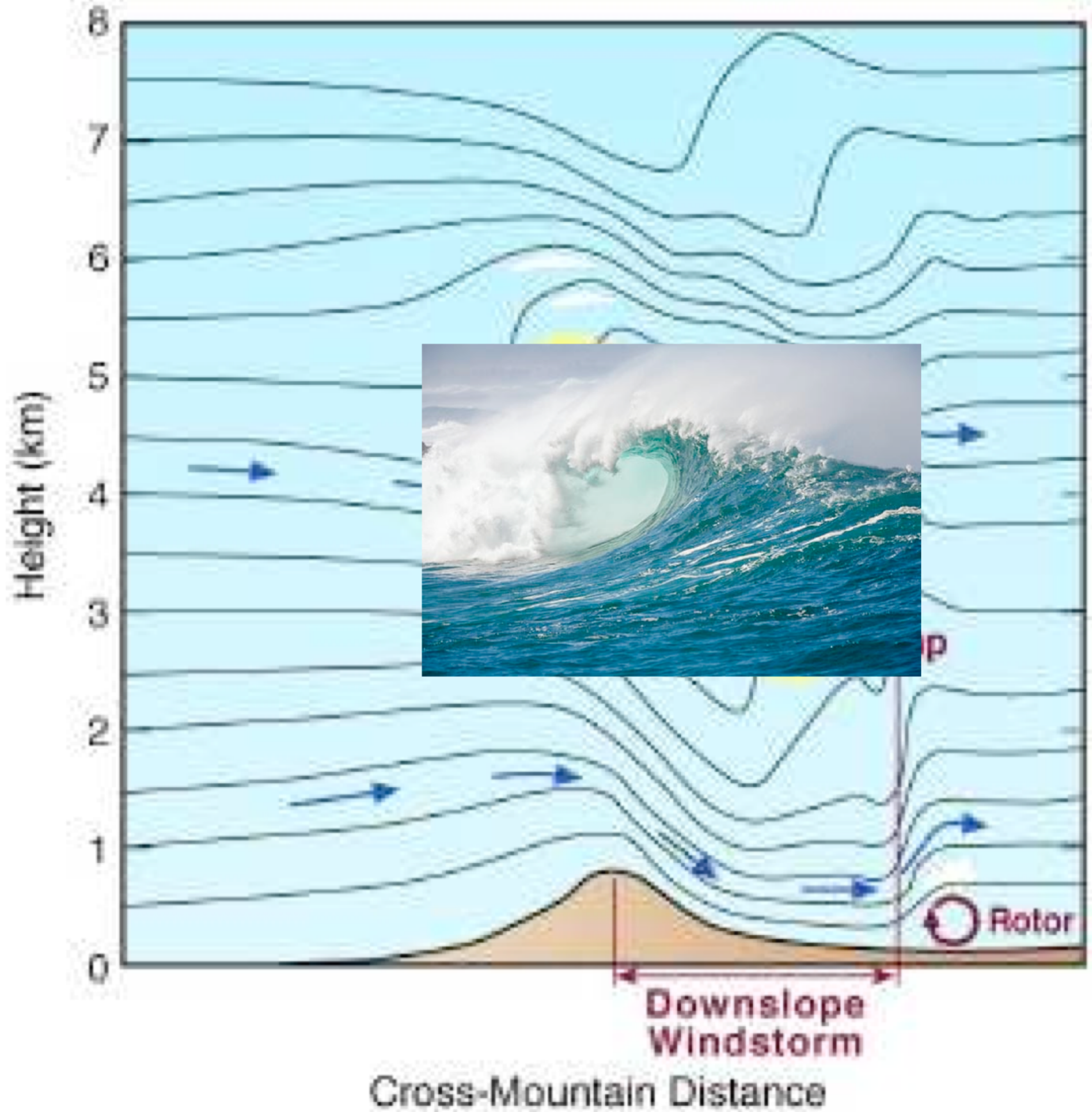
Not so obvious how to get δ from topographic data:

- RMS of subgrid topo?
- Residuals left after smoothing ?

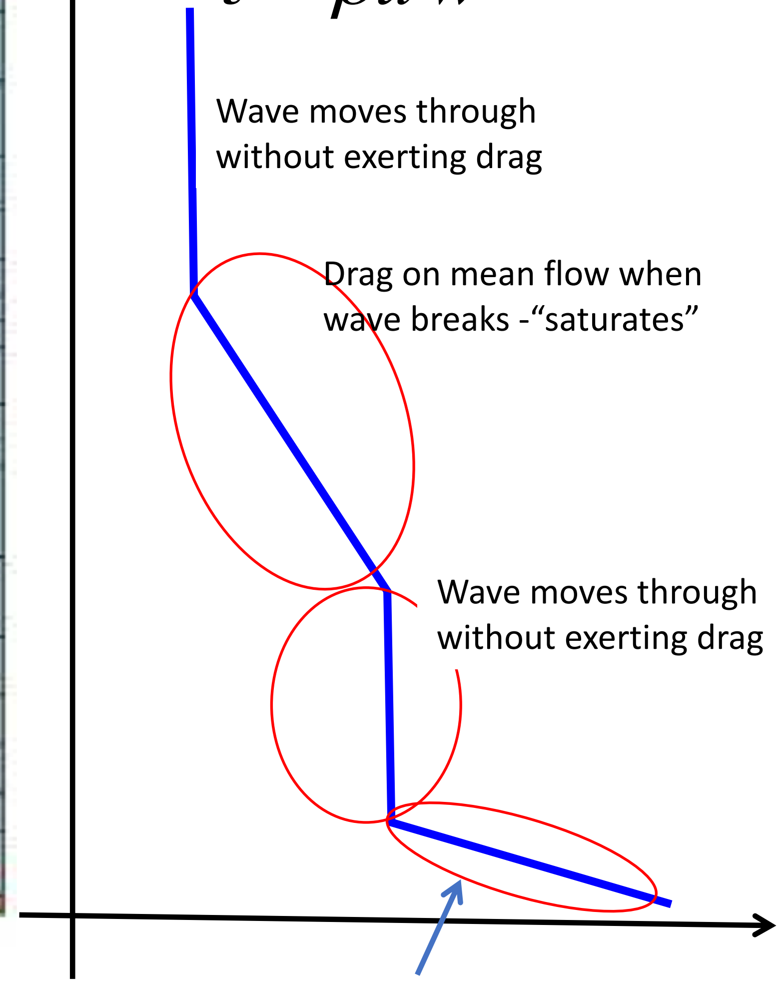




What about **"Saturation",** i.e.,wave breaking??



$$\tau = \overline{\rho u'w'}$$



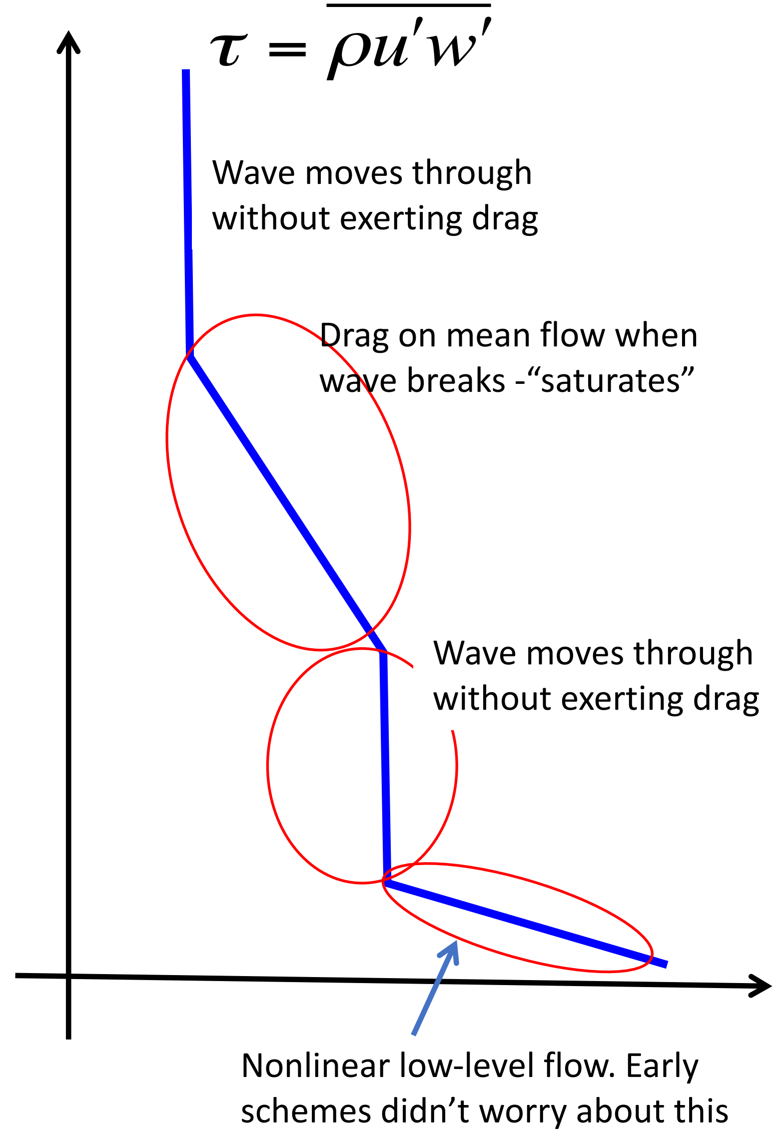
Gravity wave saturation/breaking occurs when streamlines are vertical or overturning ➔local convective instability

“Saturation hypothesis” holds that turbulence continually shaves off just enough energy to keep breaking wave exactly at edge of instability (vertical streamlines), i.e.,

Spilling breaker

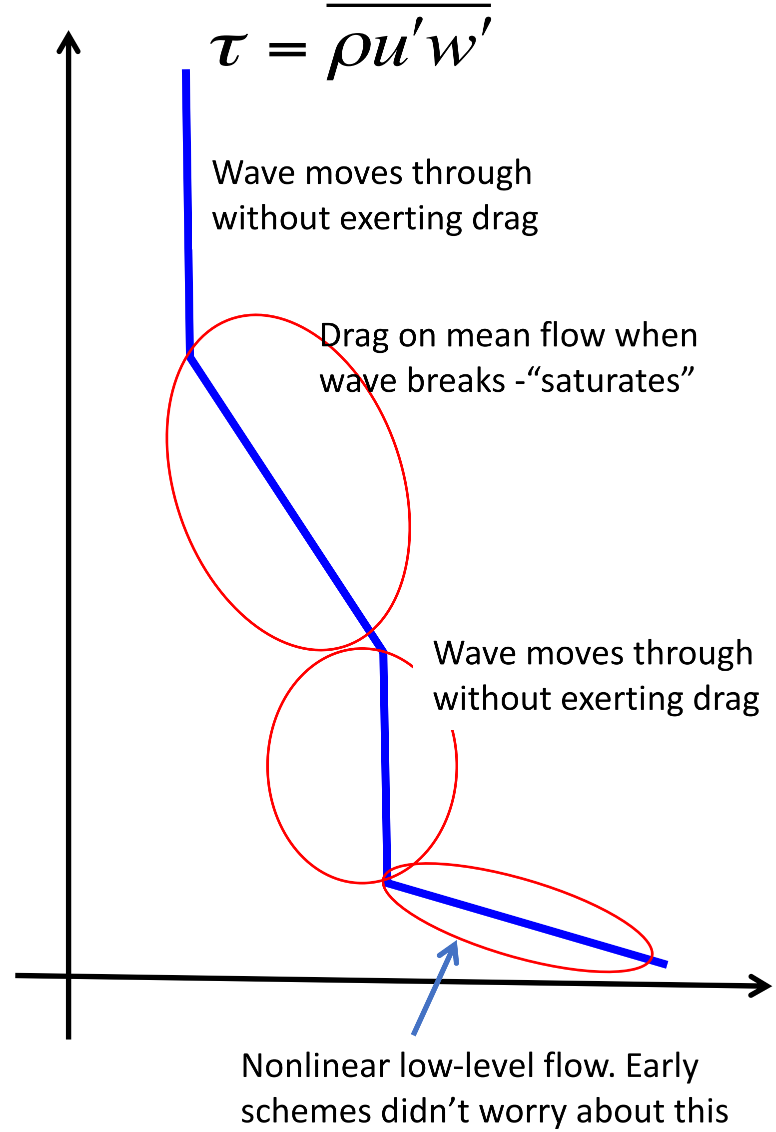
NOT

Plunging breaker



Is saturation hypothesis actually true? Probably sometimes. Not bad first guess.

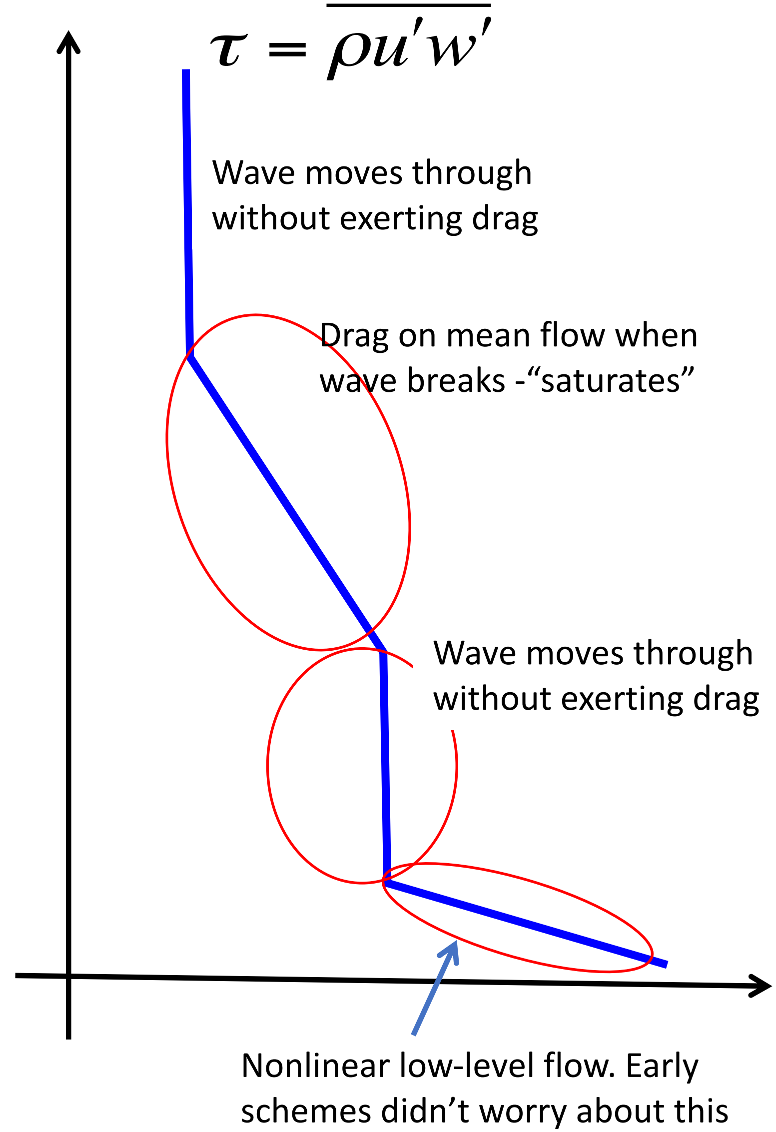
So when do gravity wave streamlines become vertical?



So when do gravity wave streamlines become vertical?

When

$$\delta = \frac{\bar{U}}{N} \quad \boldsymbol{!!}$$



Pseudocode:

At this point you have most of what you need to calculate wave momentum flux

1) Estimate $\delta(LM)$ from topography dataset

2) Calculate $\tau(LM)=\rho kUN\delta^2$

3) Advance to level above: $\tau(L-1)=\tau(L)$

4) Infer $\delta(L-1)$

5) Test for $\delta(L-1)>U/N$

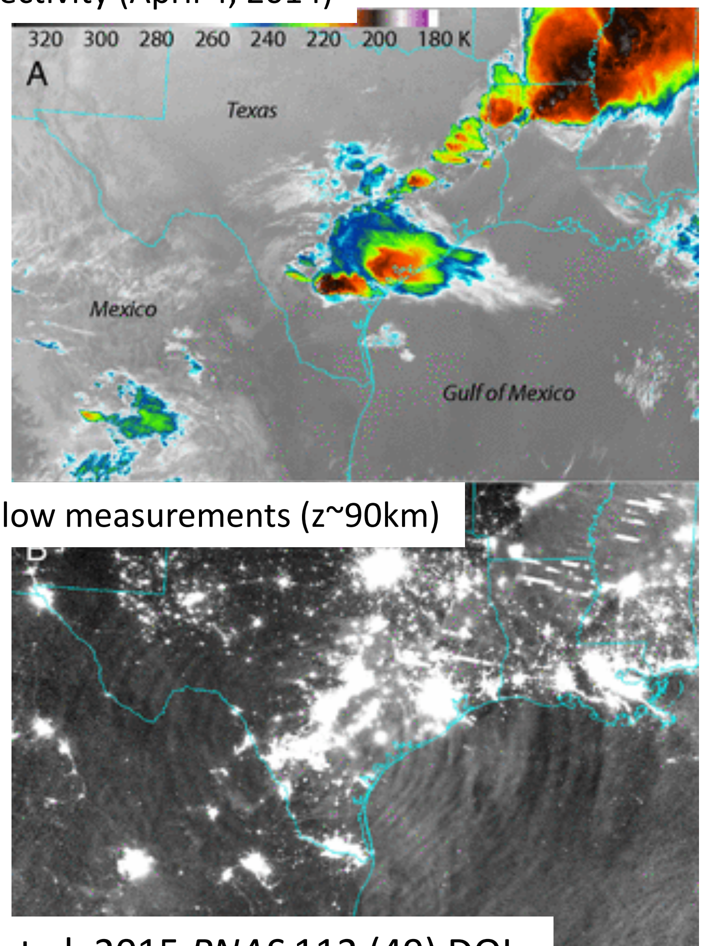
if ***no*** go to 3)

if ***yes*** set $\delta(L-1)=U/N$ recalculate $\tau(L-1)$ and go to 3)

Note: Other sources of atmospheric gravity waves exist: fronts, convection ….

Other sources: convection, fronts … …????

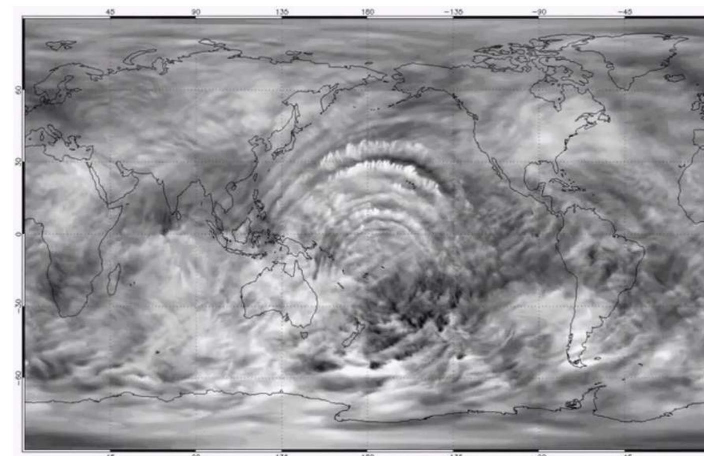
Reflectivity (April 4, 2014)



Airglow measurements (z~90km)

Miller et al. 2015 *PNAS* 112 (49) DOI: 10.1073/pnas.1508084112

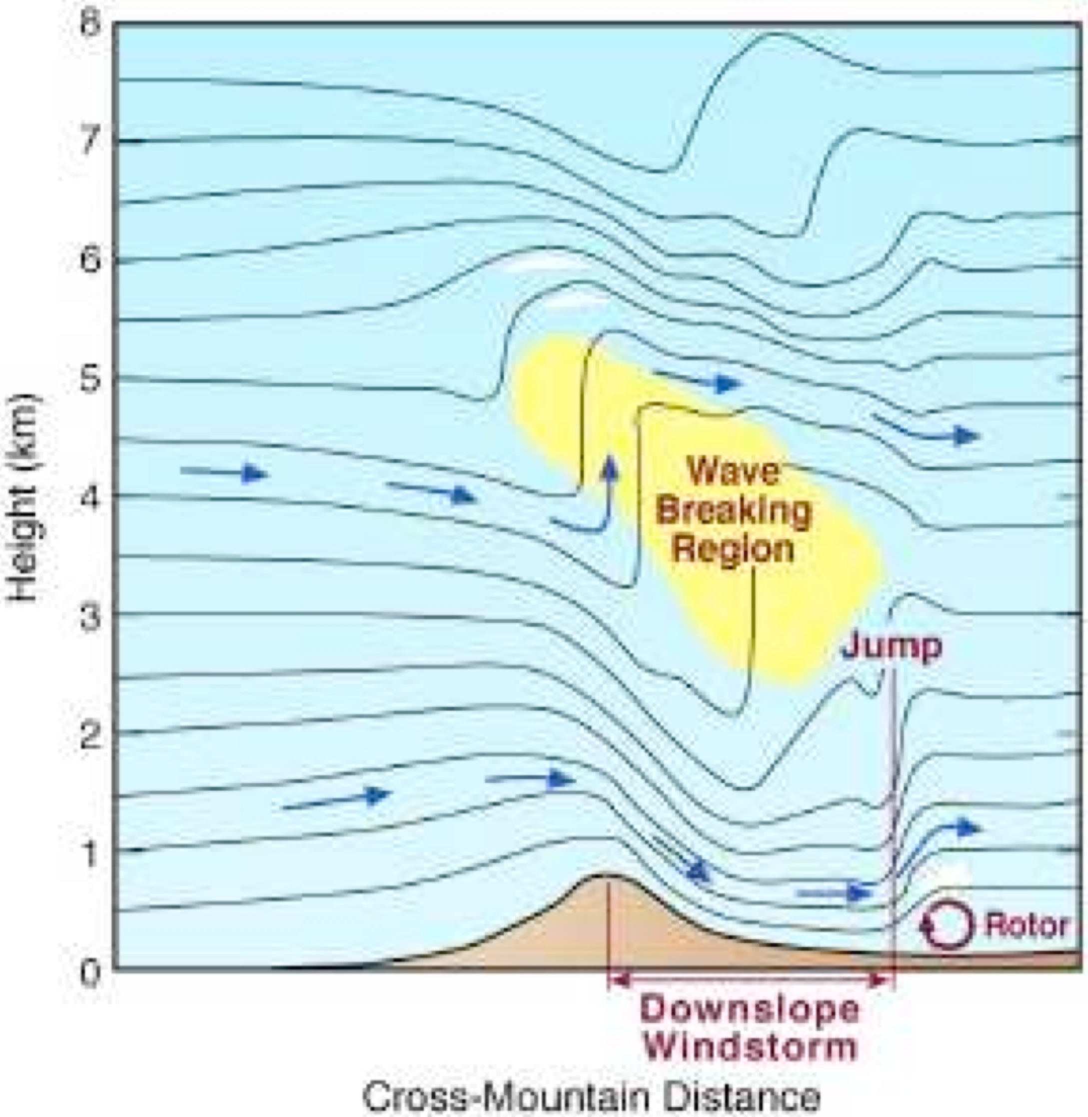
ne120 WACCM-X (Liu et al. 2014 *GRL*)



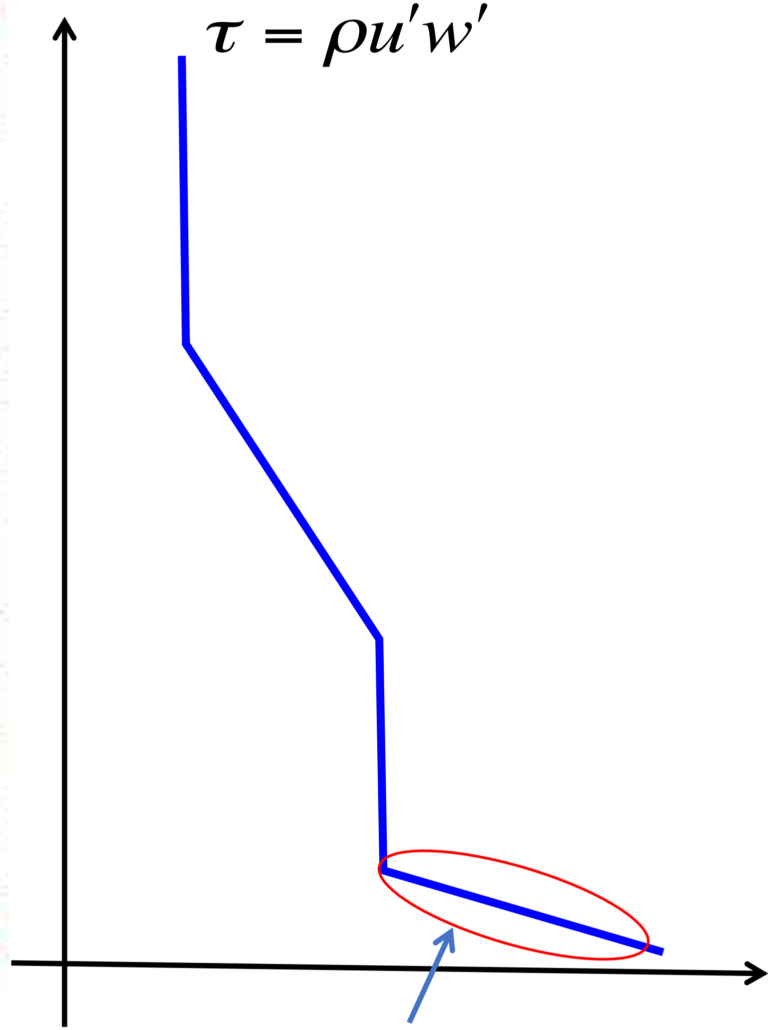
In Lindzen-type schemes like CAM's, everything described for orographic scheme maps with:

$$U \rightarrow (U-c)$$

c is wave phase speed - no longer =0 for non-orographic sources. Spectrum for *c* is specified, or derived from convective heating depth (e.g. Beres scheme).



$$\tau = \overline{\rho u' w'}$$

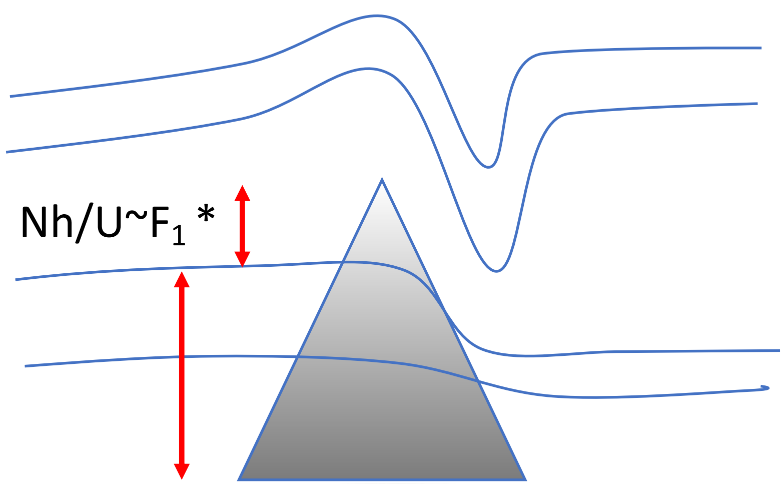


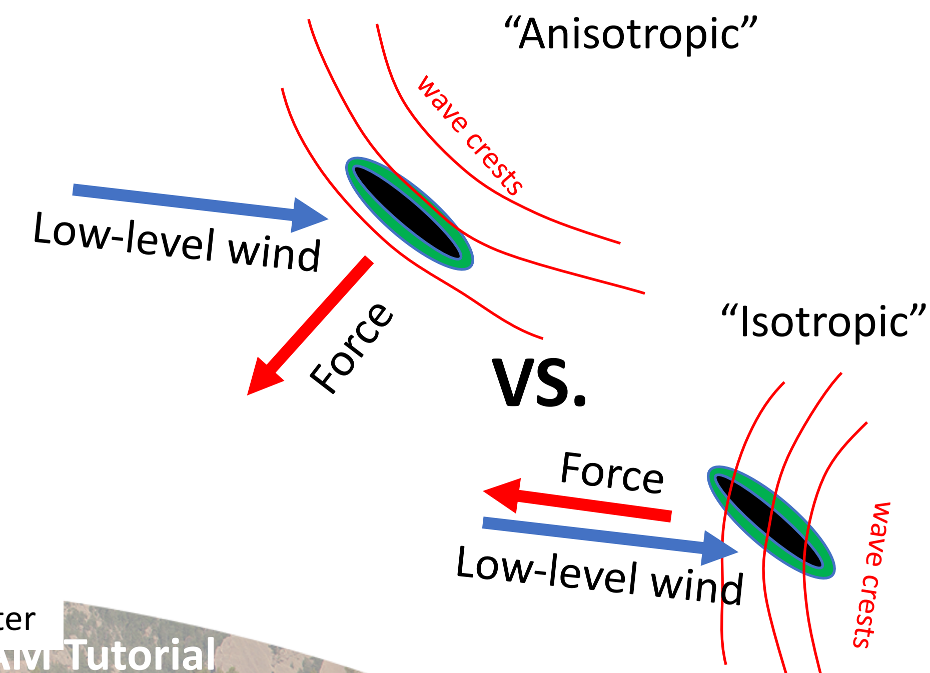
Nonlinear low-level flow. Early schemes didn't worry about this

So what about this low-level nonlinearity?

CAM6 Mountain Wave Drag scheme

- Represents flow around obstacles – *form drag* - as well as “downslope wind” high-drag dynamics (*following Scinocca&McFarlane 2000)*
- Uses topographic orientation to determine wave orientation
- Calculates forcing parameters with ridge-detection algorithm





* F_1 critical Froude number – new tunable parameter

EXERCISE

The orographic schemes discussed here rely on ”ancillary” data describing the topography

The “topofile”:

/opt/ncar/inputdata/atm/cam/topo/T42_nc3000_Co060_Fi001_PF_nullRR_Nsw042_20180111.nc

- Look at variables SGH30, SGH, MXDIS, PHIS
- What are the values for the IOP locations?

Future directions

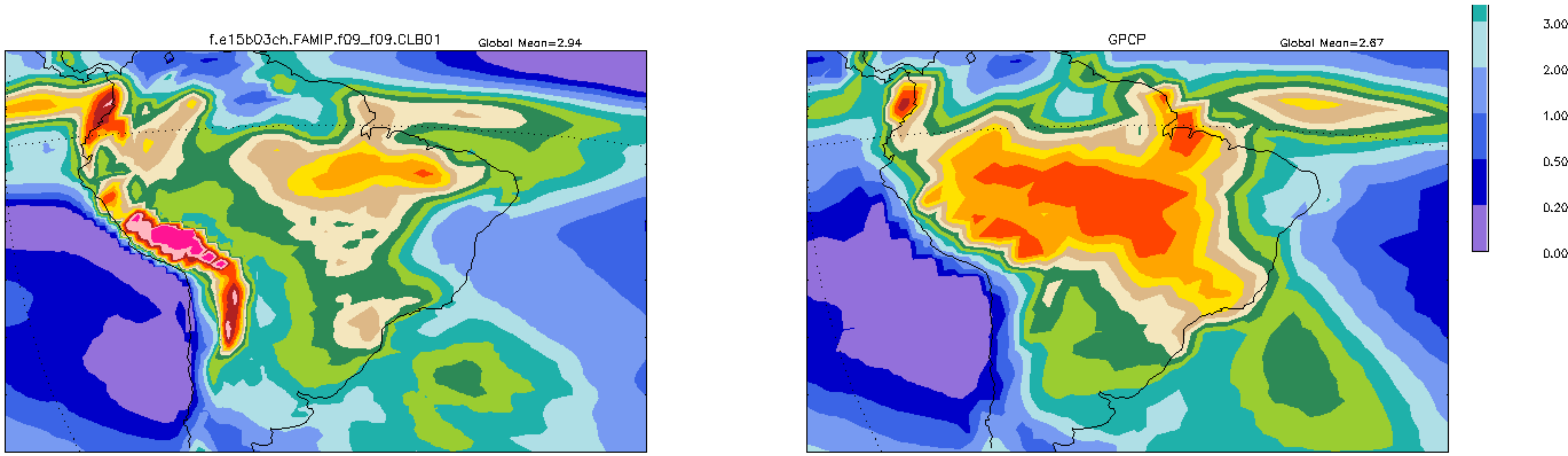
Wave cloud radiative effects and chemical effects

Nacreous ice-clouds in stratosphere

Future directions

Strong orographic precipitation biases in the tropics.

- Terrain-following coordinates to blame?
- Would introducing orographic variability into microphysics help?



A Question

At which resolution can we live without parameterizations of orographic drag

- Wave type (not 25km, … 5km?)
- PBL type (probably less than 1km)

More Questions?

Partial history of orographic drag schemes

Isotropic topography, no low-level blocking or other nonlinearities

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.

Anisotropy, low-level blocking, high-drag states

Pierrehumbert, R. T., & Wyman, B. **(1985)**. Upstream effects of mesoscale mountains. *Journal of the atmospheric sciences*, *42*(10), 977-1003.

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*.

TMS added to CAM (partially compensating for missing mesoscale drag?)

Richter, J. H., Sassi, F., & Garcia, R. R. **(2010)**. Toward a physically based gravity wave source parameterization in a general circulation model. *Journal of the Atmospheric Sciences*, *67*(1), 136-156.

Very incomplete bibliography of PBL form drag schemes

Taylor, P. A. (1977). Numerical studies of neutrally stratified planetary boundary-layer flow above gentle topography. Boundary-Layer Meteorology, 12(1), 37-60.

Wood, N., Brown, A. R., & Hewer, F. E. (2001). Parametrizing the effects of orography on the boundary layer: An alternative to effective roughness lengths. Quarterly Journal of the Royal Meteorological Society, 127(573), 759-777.

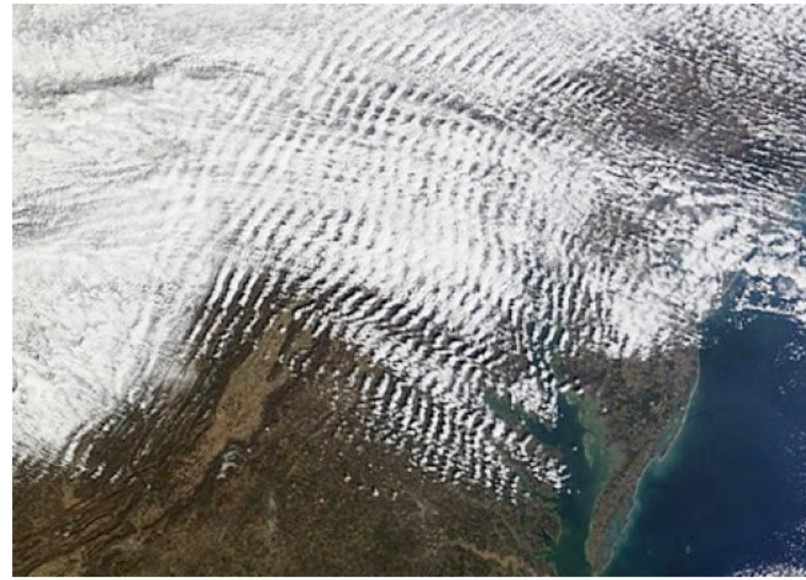
Taylor, P. A., Sykes, R. I., & Mason, P. J. (1989). On the parameterization of drag over small-scale topography in neutrally-stratified boundary-layer flow. Boundary-Layer Meteorology, 48(4), 409-422.

Beljaars, A., Brown, A. R., & Wood, N. (2004). A new parametrization of turbulent orographic form drag. Quarterly Journal of the Royal Meteorological Society, 130(599), 1327-1347.

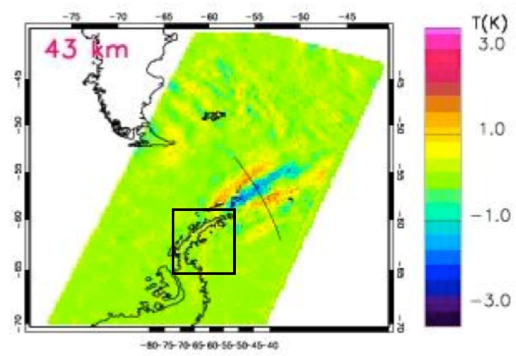
Richter, J. H., Sassi, F., & Garcia, R. R. (2010). Toward a physically based gravity wave source parameterization in a general circulation model. Journal of the Atmospheric Sciences, 67(1), 136-156.

Future directions

Trapping effects not actually included in current parameterizations.



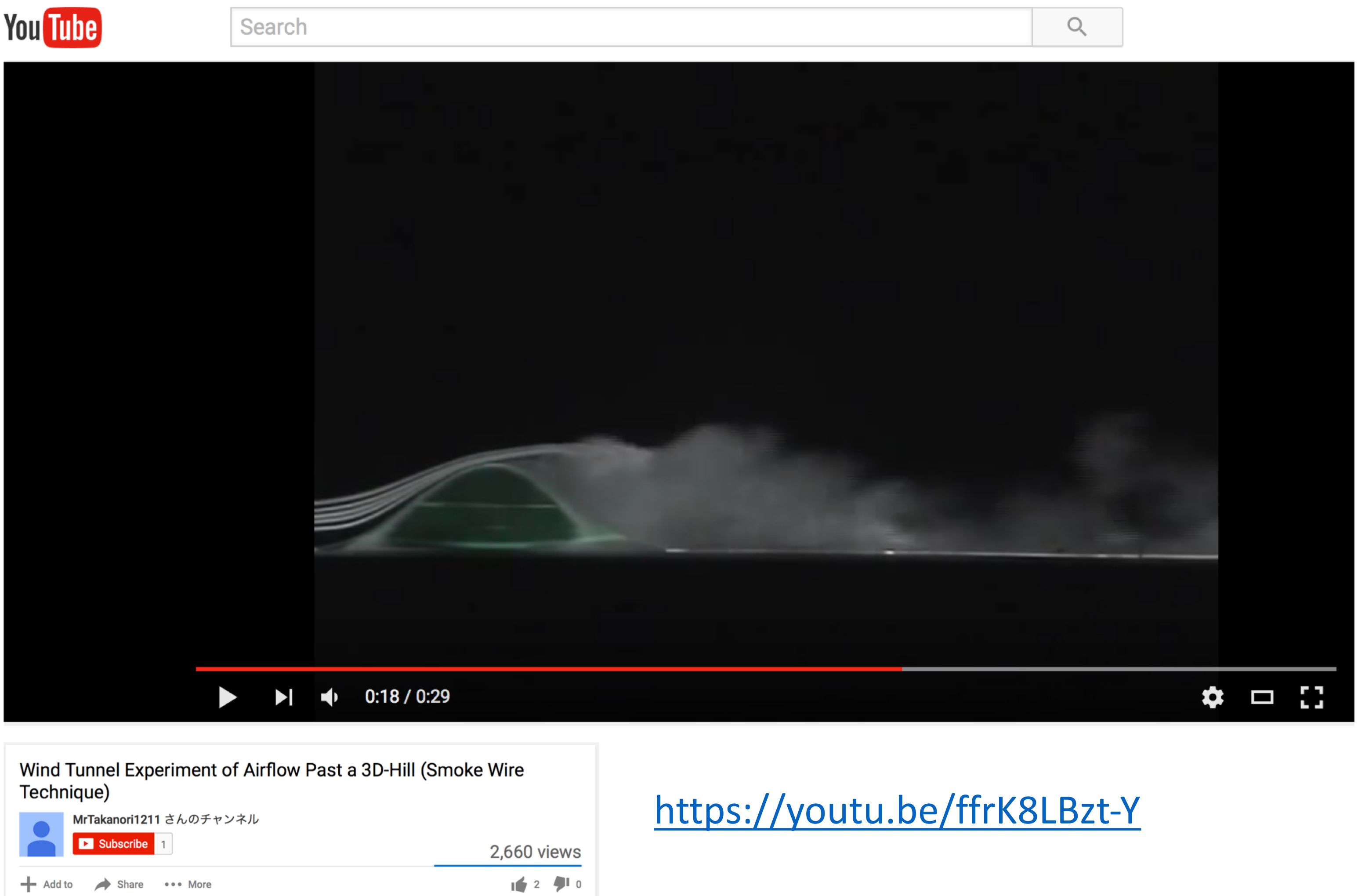
Horizontal propagation of waves across grid boxes (time-dependence also? Ray-based? Super-param.?)



PBL Form drag

- Features w/ scales <5km
- Stable stratification not necessary
- Flow separation increases form drag, but not necessary for form drag in vertical shear (Taylor et al. 1989)

$$\mathbf{F} = h_s \nabla p_s$$



https://youtu.be/ffrK8LBzt-Y

PBL Form drag

Simplest approach – enhance 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 $\sqrt{\langle h_\delta'^2 \rangle}$ where h'_δ is topographic variability for scales λ<3km-5km

PBL Form drag

More complex approach integrates over spectrum of topography (for scales below ~3km-5km). Drag from individual components decays in the vertical based on scale (Beljaars et al. 2004).

$$\mathbf{F}_x = -\alpha\,\beta\,C_{md}C_{corr}\,|\vec{U}(z)|\vec{U}(z)\,2.109\,e^{-(z/1500)^{1.5}}\,a_2 z^{-1.2}, \qquad (19)$$

$$a_2 \propto \left\langle h_\delta'^2 \right\rangle$$