A Most Fundamental Result from Satellite Scatterometry

Verification of the basic solution for the geophysical fluid flow in the Planetary Boundary Layer

R.A. Brown

Ralph Foster & Jerome Patoux

IOVWST, Barcelona May 2010

Outline for Today
20-5-2010

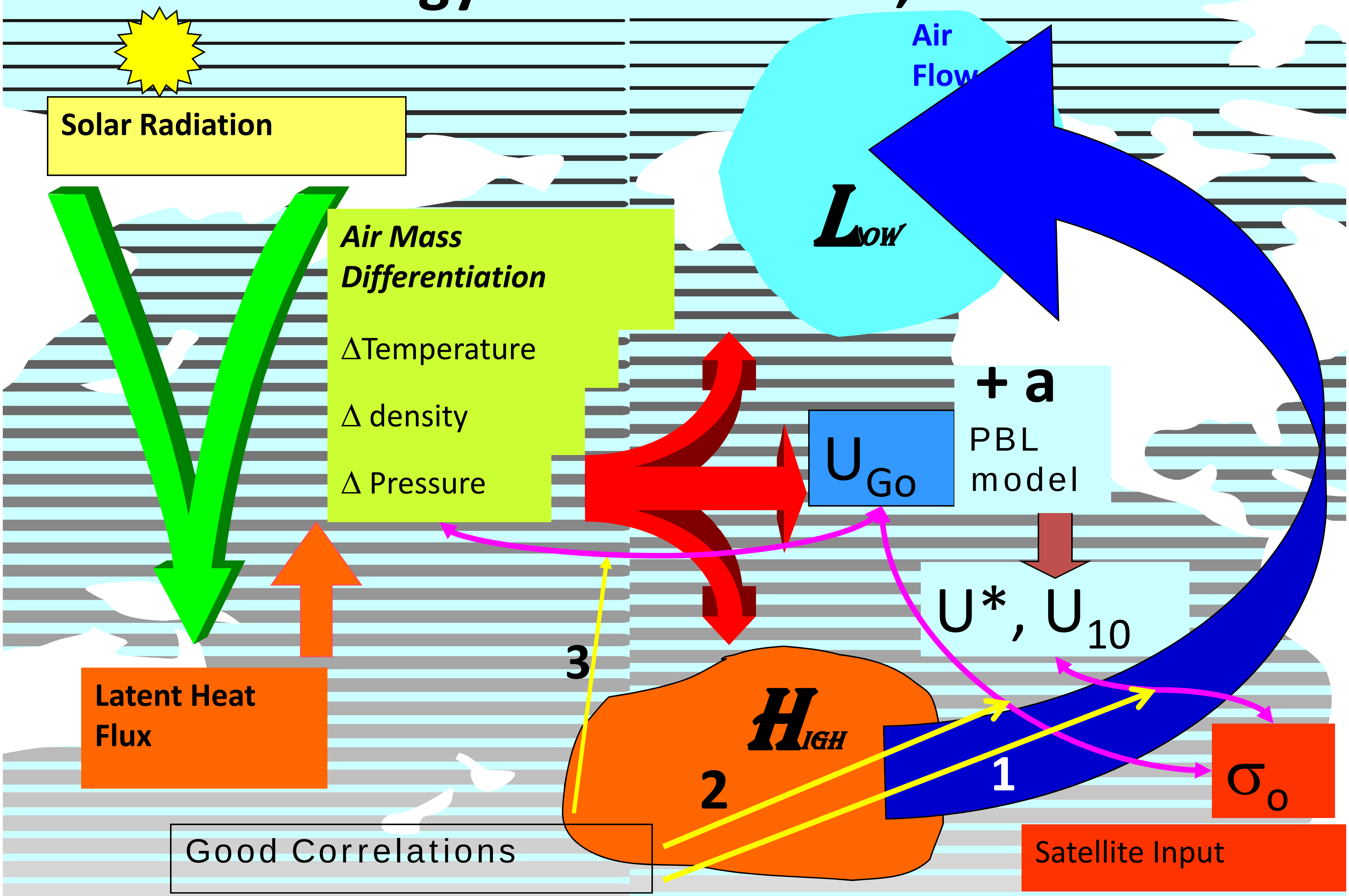
The long tedious road to winds from space

- ✓ Theory for Winds
- ✓ The Satellite Instruments
  - ✓ The scatterometer
  - ✓ The doppler lidar
  - ✓ The Synthetic Aperture Radar (SAR)
- ✓ **The Results of Winds from Space**
- ✓ **The Consequences for surface wind/flux analyses**

Why must we consider a PBL (planetary boundary layer) model?

- The satellite measures the mean density of the capillaries and short gravity waves on the ocean surface. There is no good theory relating this to anything geophysically worthwhile.
- There exists a raw empirical parameterization between surface roughness and near surface winds (for over flat, smooth land surfaces like Kansas or Wangara).
- There is a nonlinear analytic solution of the PBL in a rotating frame of reference (but it contains OLE).

Source of Energy --- for Storms, Climate



R. A. Brown 2003 U. Concepción

What does Theory say?

The analytic solution for a PBL

$fV + K U_{zz} - p_z / \rho = 0$

$fU - K V_{zz} + p_z / \rho = 0$

This linearized solution (2nd order), U (f, K,∇p) was found by Ekman in 1904.

Unfortunately, this was almost never observed

$fV + K U_{zz} - p_z/\rho = 0$

$fU - K V_{zz} + p_z/\rho = A(v_2 w_2)$

This nonlinear solution (4th order), U (f, K,∇p) found in 1970. OLE are part of the solution for 80% of observed conditions (slightly stable to unstable stratification).

Unfortunately, difficult to observe

The complete nonlinear solution (8th order) for OLE exists, including 8th order instability solution, variable roughness, stratification and baroclinicity, 1996

The solution for the PBL boundary layer (Brown, 1974, Brown and Liu, 1982), may be written

$$\mathbf{U/V_G = e^{i\alpha} - e^{-z}[e^{-iz} + ie^{iz}]\sin\alpha + U_2}$$

where $\mathbf{V_G}$ is the geostrophic wind vector, the angle between $\mathbf{U_{10}}$ and $\mathbf{V_G}$ is $\alpha[u^*, \nabla_H \mathbf{T}, (T_a - T_s,)_{PBL}]$ and the effect of the organized large eddies (OLE) in the PBL is represented by $\mathbf{U_2}(u^*, T_a - T_s, \nabla_H \mathbf{T})$

This may be written:

$$\mathbf{U/V_G} = f\{\alpha(u^*), \mathbf{U_2}(u^*), \mathbf{u^*}, z_o(u^*), \mathbf{V_T(\nabla_H T)}, \Psi(T_a - T_s), \lambda\}$$

Or

$$\mathbf{U/V_G} = f[\mathbf{u^*}, \mathbf{V}_T(\nabla_H \mathbf{T}), \Psi(T_a - T_s), \lambda, k, a] = f\{\mathbf{u^*}, \nabla_H \mathbf{T}, T_a - T_s\},$$

for λ = 0.15, k= 0.4 and a = 1; SS, neutral: $\approx f_n(\sigma_o)$

In particular,

$$V_G = f(u^*, \nabla_H T, T_a - T_s) \equiv f_n(\nabla P, \rho, f)$$

Hence $\nabla P = f_n[u^*(k, a, \lambda), \nabla_H T, T_a - T_s, \rho, f] \approx f_n(\sigma_o)$

R. A. Brown 2010

Published Questions asked of PBL Modellers

- **Why are you publishing papers where the Navier-Stokes equations are being used for turbulence, where they are invalid?**

  Bound.-Layer Meteor. 1976; Fluid Mechanics of the Atmosphere, 1991

- **Why are you using a procedure (Higher Order Closure) that failed observationally and mathematically in classical fluid mechanics?** *Turbulence & Diffusion Meeting, 1974; The Global Atmos. & Ocean Systems,* 1994

- **Why are you using K-theory when it is invalid in a large-eddy environment?** *Turbulence & Diffusion Meeting, 1974; Bound.-Layer Meteor. 1976; Fluid Mechanics of the Atmosphere, 1991; The Global Atmos. & Ocean Systems, 1994.*

TURBULENCE & Approximations in the boundary layer

MODEL	# Layers	Comment
Analytic PBL Inversion,	0	U = f(U_G, λ, $T_a - T_s$, ∇T_a) **K-Theory for small eddies** or, **Explicit Large eddies**
Numerical PBL LES Re #, Domain Limited	50	Equator, Inversion, limited **K-Theory for small eddies** **Explicit Large eddies**
GCM PBL	5	Bad (no OLE,LES) **K-Theory for all eddies** ($K + K_{ole}$)
All land empirical formulas		Fluxes (u*) depend on **Bulk Coefficients for Fluxes** **Surface Layer Approximations**.

R. A. Brown 2010

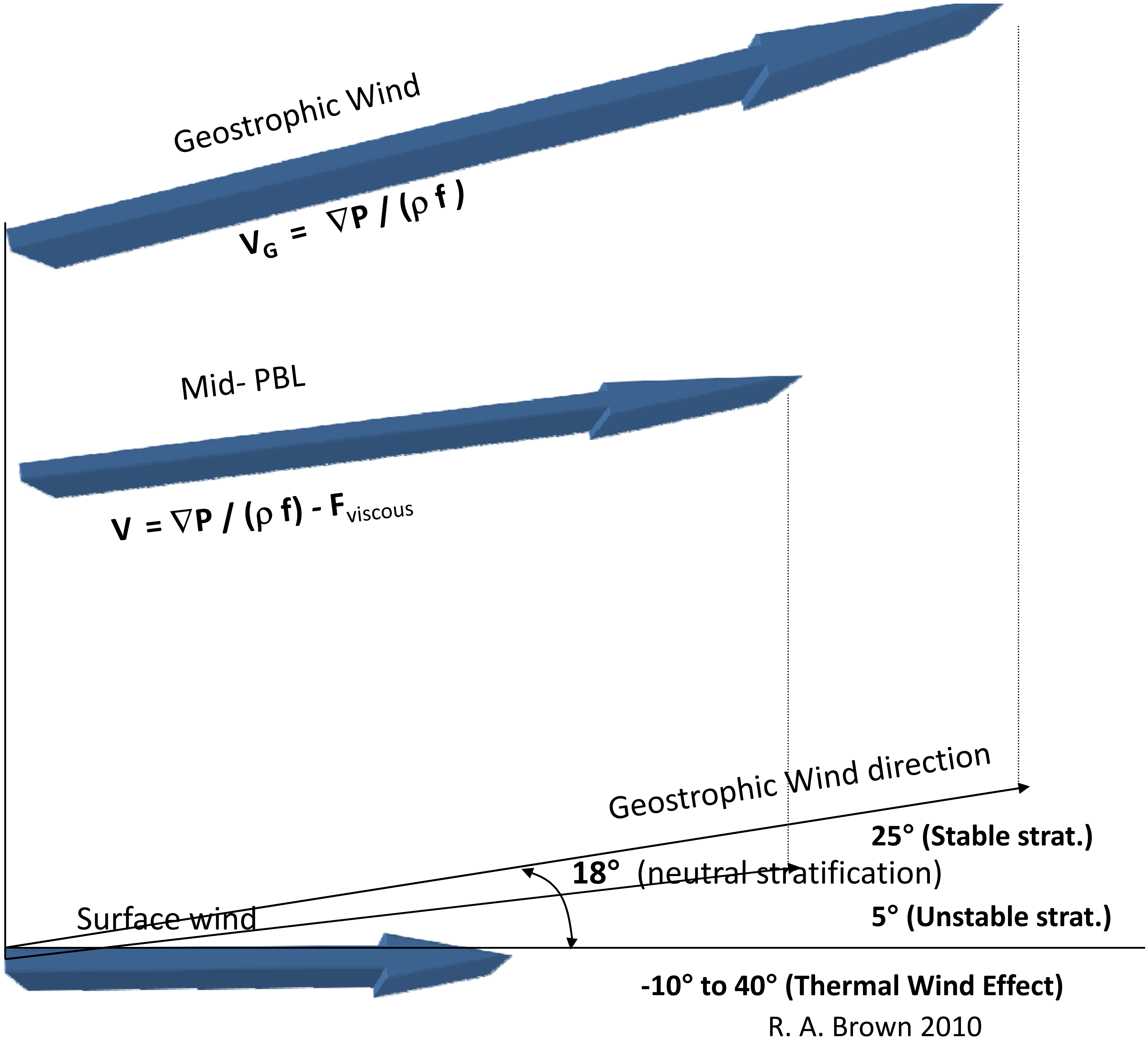
On the History of the Mathematical solution for the flow in the boundary layer with a rotating frame of reference (a PBL)

- 1960s: The Ekman PBL is unstable to infinitesimal perturbations --- Stop using the linear diffusion model (Ekman solution!). It is only an approximation (bad w/LE).
- 1970: The analytic PBL solution is a modified Ekman solution based on a rough K-theory for *small-scale* turbulence plus a large-scale coherent structure [Organized Large Eddies (OLE) = 'Rolls'].

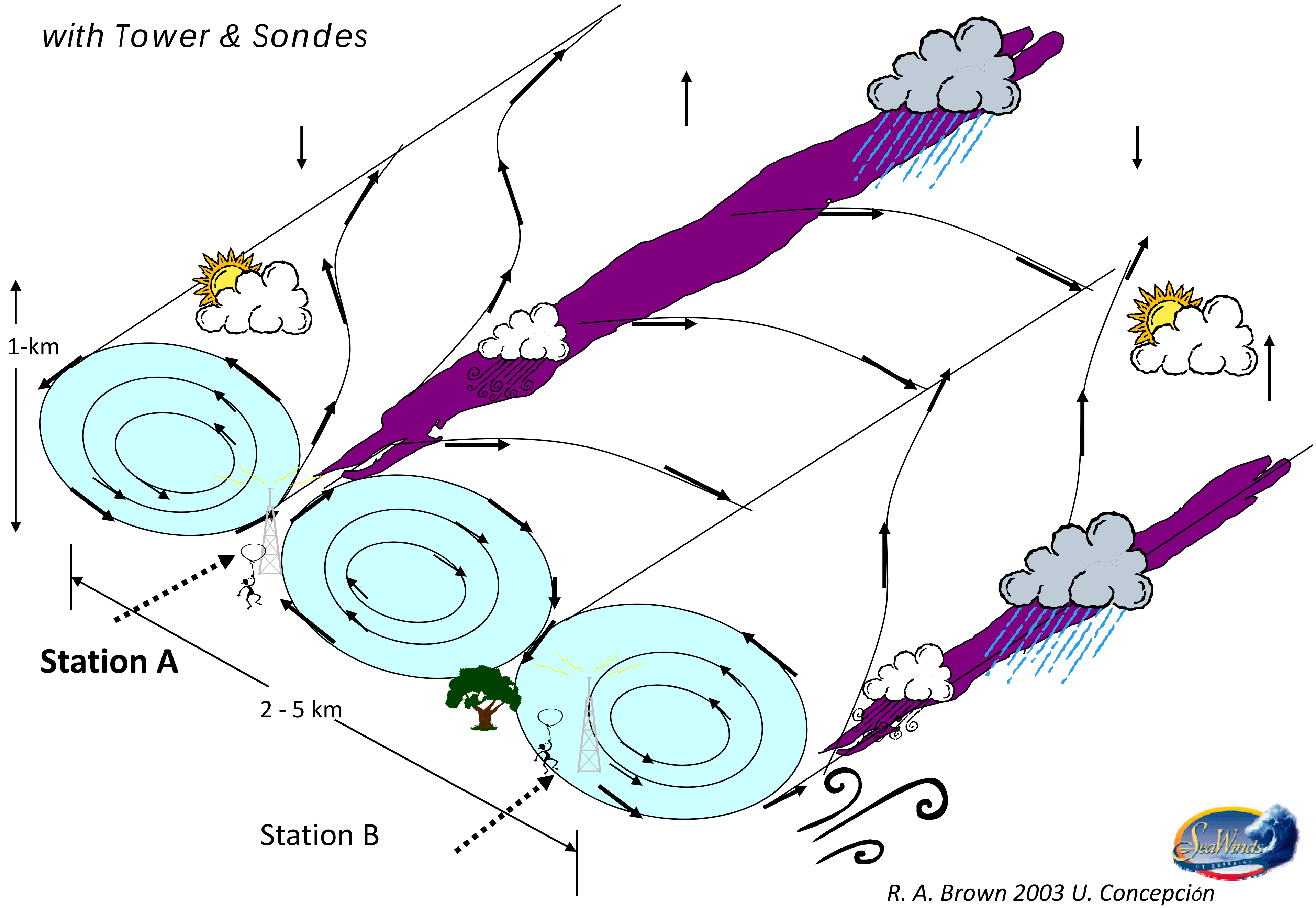
  [2006, see Ralph Foster: ralph@apl.washington.edu & pbl.atmos.washington.edu]
- 2000s: Applications in NCEP & NASA PBL models using simple parameterizations (*Rolls for Dummies*)

  [see Jerome Patoux: jerome@washington.edu]

R. A. Brown 2008


Geostrophic Wind
V_G = ∇P / (ρ f)
Mid- PBL
V = ∇P / (ρ f) - F_viscous
Geostrophic Wind direction
25° (Stable strat.)
18° (neutral stratification)
5° (Unstable strat.)
Surface wind
-10° to 40° (Thermal Wind Effect)
R. A. Brown 2010

Taking measurements in the Rolls with Tower & Sondes



Involvement with PBL Winds --- Bob Brown

- PBL theorist: PhD **Thesis** "*Rolls theory --- the end of diffusion **models** for 'heat flow' to the atmosphere*".
- **AIDJEX** Project, developed: "*A two-layer single similarity parameter PBL **Model** with Rolls*" (much better than diffusion)
- **SeaSat Satellite** '78: Show that getting U_{10} to ±0.1 m/s from 800km away is impossible ---- "*We can't verify it or believe it.*"
- The Scatterometer as an Anemometer. *J. Geophys. Res*., **88**, C3, 1663-1673, 1983 "*U_{10} to ±1 m/s is good enough for a lot of science.*"
- **PI** for: Scatterometers (SASS, ERS1/2, NSCAT, QuikScat, SeaWinds); Lidars: (LAWS, Sparkle, Aladin); Radiometers; (SMMR, SSMI); 1978 - present "*It's a great job & someone gets to do it.*"

Questions asked of OLE Modellers

So large-eddies muck up the PBL models used in GCMs. How often are they there? *AMS T & D, 1978; NMC 1994.*

Well, for one thing, they have a lot of names…

Large-eddies

finite perturbation secondary flows

Rolls

Coherent Structures

Counter-rotating helical roll vortices

Organized large eddies (OLE)

Random and organized secondary flows

Cloud streets, windrows, slicks & seif sand dunes

Turbulence ?

R. A. Brown 2010

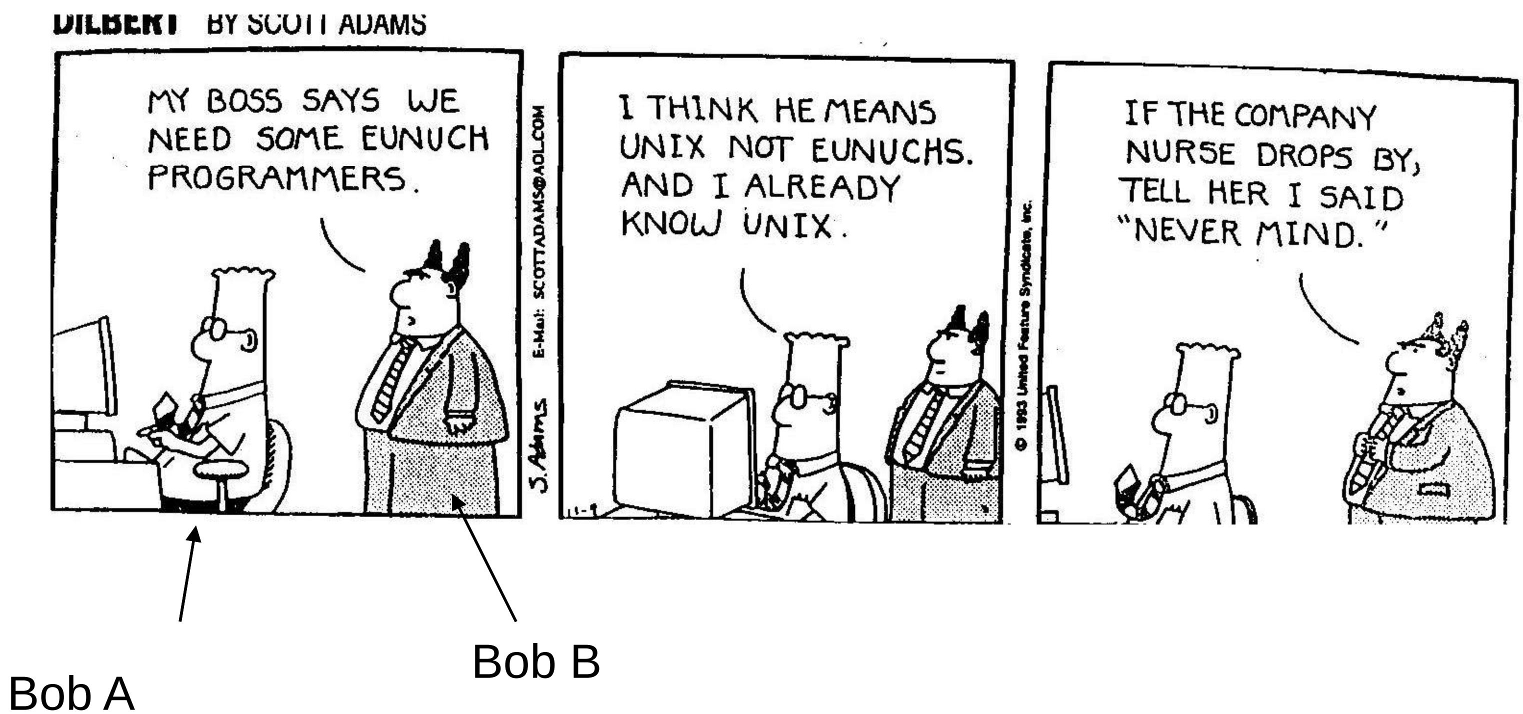
And a lot of Observations:

K-Theory Vs Similarity

- 1970: OLE is just a complicated theory for cloud streets
  - 1974 “Single parameter Similarity Model w/OLE is just a theory” [*so is gravity, evolution…..]*
  - 1977 “OK. They also occur in numerical models and a few experiments. And, if the theory is correct, diffusion models (used in all GCMs) have wrong physics. But, how often are OLE present globally? Need data not just theory”
  - 1978. Seasat SAR shows OLE surface imprints, often.
- 1980: OLE do occur. Analytically, Numerically, and Observations --- and they all look similar.
- 1998: SAR (RADARSAT) shows OLE produce signature on ocean surface stats ~ 80% of the time

HOC vs Analytic PBL Models

- Current GCMs all have versions of HOC PBL models (Modified linear K-theory)
- Large-eddies cannot appear in HOC models at GCM resolution
- Large-eddies are present in the PBL routinely (from SAR pictures)
- Current GCMs have wrong PBL physics, errors in Surface Winds


DILBERT BY SCOTT ADAMS
MY BOSS SAYS WE NEED SOME EUNUCH PROGRAMMERS.
E-Mail: SCOTTADAMS@AOL.COM
S. Adams
I THINK HE MEANS UNIX NOT EUNUCHS. AND I ALREADY KNOW UNIX.
© 1993 United Feature Syndicate, Inc.
IF THE COMPANY NURSE DROPS BY, TELL HER I SAID "NEVER MIND."
Bob A
Bob B

Revelations from scatterometers using the nonlinear PBL model

* Ship or Buoy winds are not good surface truth in general. Hence the climate record is incorrect.

* Weather & climate PBL models have the wrong physics.

* The winds are higher, the low pressures are lower & more frequent, heat fluxes are greater and stress much greater than climatology states. Climate modelers take note. Data on storms and fronts is revolutionary. (Patoux, J., G.J. Hakim and R.A. Brown, 2004: Diagnosis of frontal instabilities over the Southern Ocean, *Monthly Weather Review*)

* The good news is that scat (+ SAR; + doppler lidar) winds are the best bet for getting good models of the weather & climate

Conclusions

- The nonlinear PBL model with variable turning (stratification, wind speed) provided good surface truth for the model functions (1978)
- The Scatterometer winds plus SAR winds showed that the nonlinear model is the correct common PBL solution (per the mathematics) (1980)
- The nonlinear PBL sensitivity to thermal stratification (Ta – Ts) and thermal wind [T(x,y)] offer better, smoother wind fields via Surface Pressure; better details of wind and flux parameters; better inputs to numerical models. (2010)

End

Satellite Observations

In the beginning there exists a measurement

Emissivity (radiometer, SMMR, SSMI….)

backscatter (σ_o) (SASS. SAR. Alt.)

Doppler (lidars)

R. A. Brown 2008

1978 - SeaSat

Scatterometer Products from Space

Marine Surface

WIND vectors

Surface stress vector

2008

Scatterometer Products From Space-*Marine Surface*

Needs BL model

WIND vectors

Pressure Fields

Mean PBL temperature

Surface stress vector

Mean PBL stratification

Fronts

Storms: Location Strength

Pack Ice location, concentration, thickness

Land Vegetation

Boundary Layer Equations

$$\mathbf{V}_t + \mathbf{V} \bullet \nabla \mathbf{V} + f(\mathbf{k} \times \mathbf{V}) + \nabla P/\rho + \mathbf{A}(z) = 0$$

or

$$U_t + (KU_z)_z + f\,V - P_y/\rho = 0$$

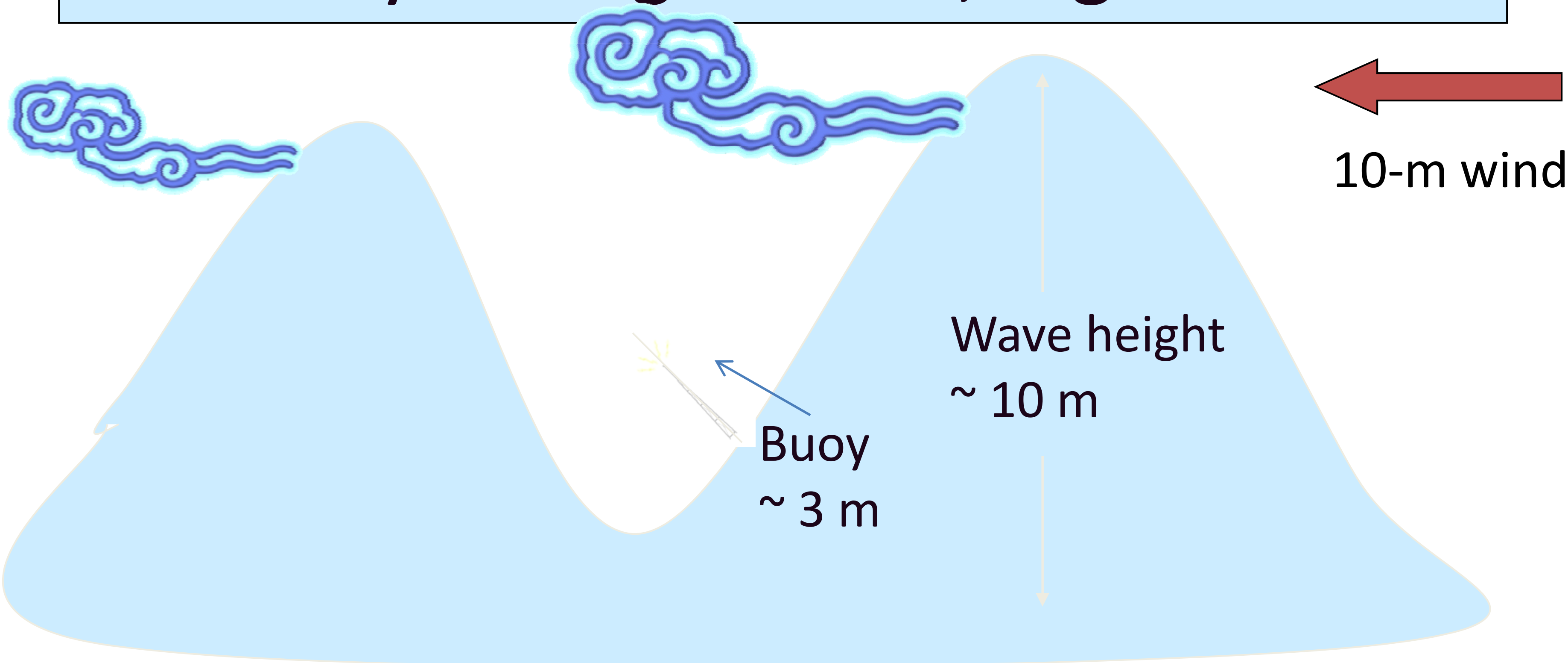
$$V_t + (KV_z)_z - f\,U + P_x/\rho = A(\overline{u_2 w_2})$$

Small-scale eddy momentum flux

Large-scale eddy = OLE momentum flux

R. A. Brown 2003 U. Concepción

The buoys in high winds, high seas



Sheltering: The high waves place the buoy in shelter and/or turbulent wake of the waves yielding low winds

Displacement height: When surrounding topography is rough, the sensor is 'displaced' downward to reflect its lower position in a more turbulent boundary layer =lower winds

Practical Aspects of a Geostrophic Wind Model Function

*(implied Surface **Pressure fields**)*

<u>Surface 'Truth' Limits (pressure fields)</u>

<u>Buoy and ship pressures</u>: Sparce but accurate in low and high wind regimes.

<u>GCM</u>: Good verification; compatible scale

Who Killed the Scatterometer?

- If you saw the movie, “Who Killed the Electric Car?”, then you might understand this question. The similarities are many. In fact, I might suggest that it was the same people.

Introduction to Satellite determined winds

Businger to Brown in meeting with Jet Propulsion Lab guy, 1978: "They're putting up a satellite that measures small-scale surface wave roughness. You're a fluiddynamicist, we'd like the solution to the relation between the surface wind and the wave generation"

(*I knew that every mariner knows this relation;*
I also knew that no scientist can solve for it.)

Brown to Businger: "OK" (*It's Quixotic, but it's a living*)

Bottom line: (30 years later) There still is no theory. However, in the best tradition of Atmospheric Science --- there is a curve fit. What more do you want?

Curve Fit: When there's no physics understanding of how two things are related, you can measure each of them together and plot them. If they move together you can draw a curve thru the graph. Then if you measure one, you can get the other.

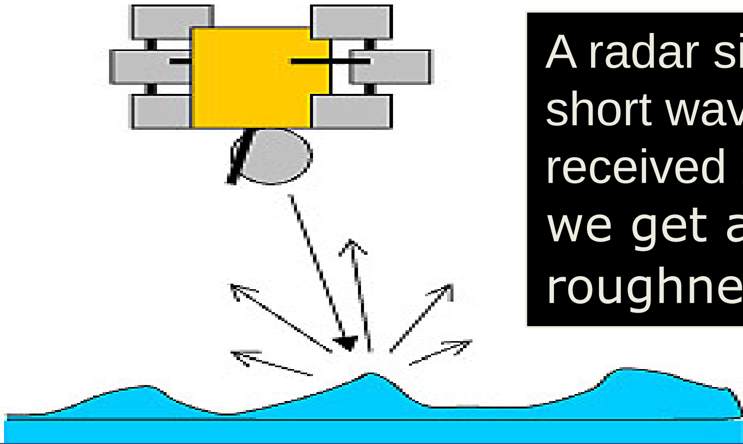
Epilogue: The Satellite Data Proved Roll Theory

Practical Aspects of Wind Measurements available for parameterization with σ_o
<u>Surface 'Truth' Limits</u>

<u>Ship winds</u>: Sparse and inaccurate (except some Met. Ships).

<u>Buoy winds</u>: Sparse; a point. They tilt; have variable height - miss high winds and low wind directions.

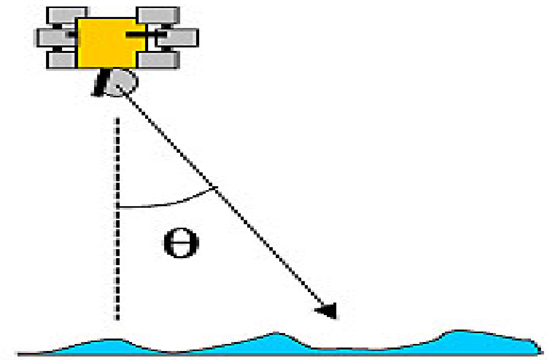
<u>GCM winds</u>: Inaccurate physics in PBL Models; Too low high winds, too high low winds. Resolution coarse (getting better).

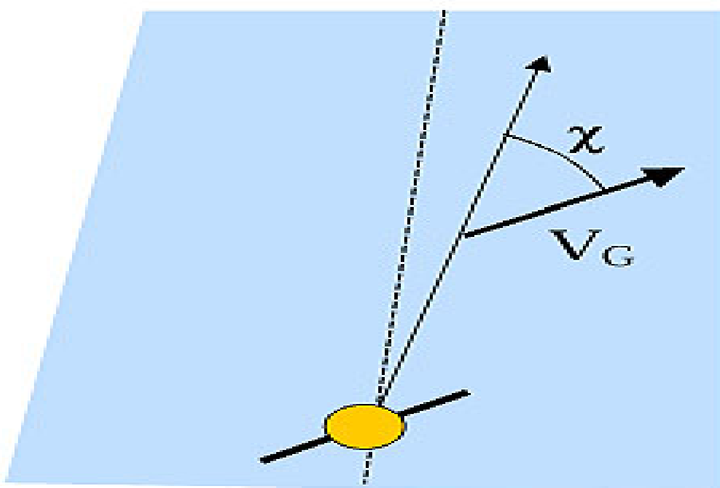


A radar signal is sent to the surface. It bounces off short waves (2-6cm). The microwave energy received back at the satellite is the signal σ_o. Thus we get a measure of the small-scale roughness. Sailors know this is $\propto$ windspeed

But it also depends on:

Incidence angle θ
Angle between the radar look and the vertical [redacted]





Azimuth angle χ
Angle between the radar look and the geostrophic wind

R. A. Brown 2007 Lidar Miami

UW; Patoux, '03

Revelations ***1***

Compared to what is found in GCMs and climatology records, Storms are:

- Often misplaced
- Stronger (deeper Pressures)
- More frequent

- And, as (if) we get a longer data record, getting stronger and/or more frequent

R. A. Brown 1/2008

Revelations 3

- Fronts; new concepts
- --- Defined as lines of different sea state (roughness variation) => wind change

These fronts are:

- Ubiquitous
- Persistent
- Mysterious (e.g. no storm in sight)

R. A. Brown 1/2000; 2008

Atmospheric Flow --- the basic equations

$\Sigma F = ma$ (Is there an eddy-turbulent continuum?);

$\Sigma F = 0$ (Is there steady-state?);

$\Sigma F = \nabla P - \rho f V_G = 0$ (Rotating FOE --- add a Virtual Coriolis Force, $f V_G$)

This Inviscid, Barotropic model makes a decent GCM. ....

(to get surface winds; Add the boundary condition --- get the PBL)

$\Sigma F = \nabla P - \rho f V_G + F_{viscous} = 0$

<u>Winds</u>

GCM (freestream): $V_G = \nabla P / (\rho f)$

w/PBL: $V = \nabla P / (\rho f) - F(z)_{viscous} / (\rho f)$

Surface Layer: $V/u^* = k [\ln z/z_o + \Psi]$ (Stratification Ψ, roughness, $z_{o,}$ von Karman k)

R. A. Brown 2010

Revelations 1 via PBL model

- **There exist large regions of High Winds ($1000\ km^2$/storm)**

  that nobody knows of……
- These do not appear in:
- GCM analyses
- Buoy data
- Climate data

R. A. Brown 1/2000; 2008

Revelations 2 via PBL model

- Real time forecasts (NCEP) are improved using Quikscat surface pressure fields

R. A. Brown 2010