Atmospheric Processes: Modelling and Analysis

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SCOPE OF THE PRESENTATION

Atmospheric Processes: Modelling and Analysis:

TALKING TO THE "CIVIL ENGINEERS" ON

AIR QUALITY MONITORING AND ASSESSMENT

STORY TIME: Starting from the "Scratch"

Brief Introduction to the Topic of Presentation

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Atmospheric Modelling: An Introduction

Explaining the Concepts of "Modelling" to Layman)

==

"Air-Quality" aspects in Atmospheric Modelling

Challengs Ahead ...

==

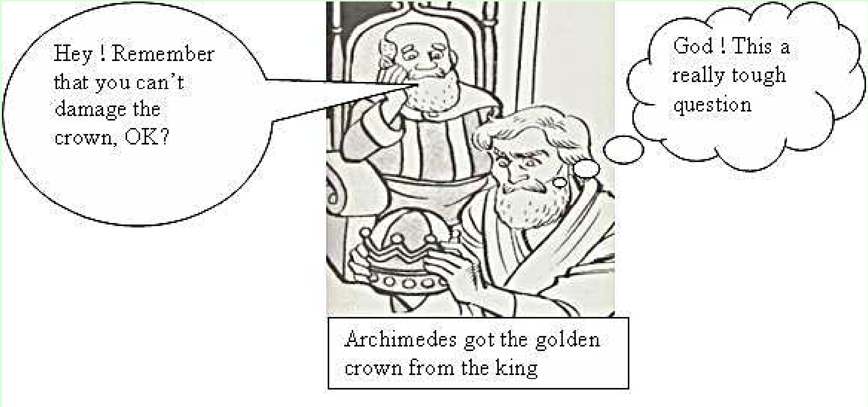
The Story Begins: Once upon a time .....

King Hiero-II: ($\sim$ 275- 215 BC): the Famous Greek Emperor

Long time ago kind Hiero ruled the kingdom of Syracuse. After gaining power, the king wanted to pay tribute to gods. He asked a goldsmith to craft a golden crown that he would place in a temple. He carefully weighed and gave a precise amount to the goldsmith. The goldsmith did an excellent job. He created a beautiful crown of golden leaves, and returned it to the king in right time. The king was very happy. He weighted the crown and saw that the weight was same as that the gold he had provided. Later on however the king suspected that goldsmith had not used all gold that he gave him, but had mixed a little silver while making the crown. So the king thrown an open challenge to his ministers and other sub-ordinates to cross-check the purity of the crown without damaging the crown itself.

IT WAS INDEED A BIG CHALLENGE ...($\sim$ 250 BC)

Archimedes (a mathematician by profession) accepted the Challenge...



Eureka! Eureka! Eureka! ... A Beginning

GREAT IDEAS COME JUST LIKE THAT ...(∼ 250 BC)

The crown and the gold have equal weight.

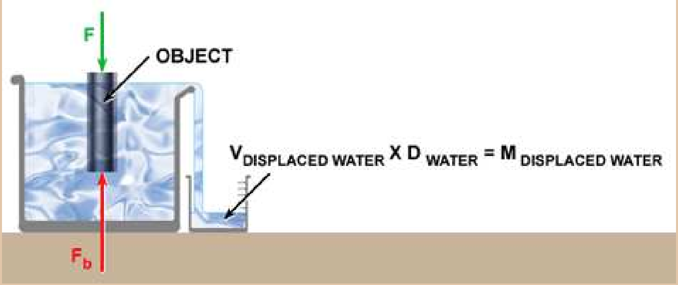
The crown displaced more water than the gold.

Archimedes knew that gold and silver have different densities, meaning that if you take lumps of similar sizes gold and silver, the lump of gold would be almost double in weight as silver is lighter than gold.

While he was still pondering on the matter, Archimedes went to a public bath to relax. When he stepped in the tub of water, he saw that some water spilled out of the tub. Then the more his body sank in the tub, more water ran out. All of a sudden Archimedes had a bright idea and he started running home without wearing his clothes, shouting Eureka! Eureka! Eureka!

Beginning of a New Era in the Fluid Studies

Some of the famous Cartoons on Archimedes ($\sim$ 287 - 212 BC)



The evolution of Archimedes's Principle was probably one of the major milestones in the beginning of the Fluid Statics. As I just now mentioned.....it was just a beginning.

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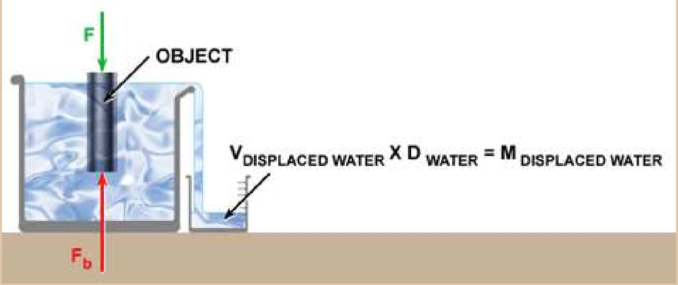
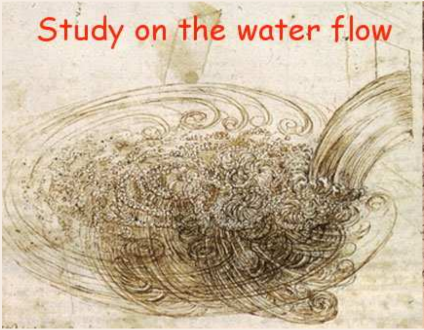


Just on the lighter side: **Corruption is not a new-generation disease; but we are only carrying the corrupt genes given to us by our ancestors, which were given to them by their ancestors...**

No Controversy Here: Leonardo da Vinci (1452 - 1519)

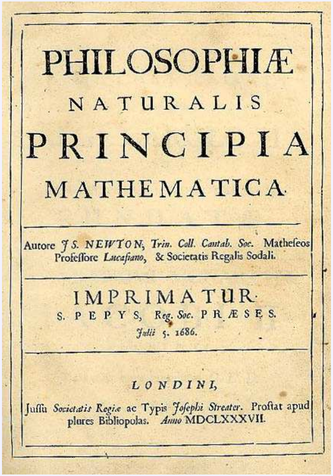
A Big Picture was yet to come up...but the process had already began

After a careful examination on the behaviour of fluids, Leonardo da Vinci had drawn sketches of complex flows over objects in streams. At that time, nobody ever knew that - his sketches would draw further attention of the scientists of new generations.



Sir Issac Newton's Era (1642 - 1727)

Principia Mathematica: A Milestone in the Seventeenth Century


PHILOSOPHIÆ
NATURALIS
PRINCIPIA
MATHEMATICA

Autore *J. S. NEWTON*, *Trin. Coll. Cantab. Soc.* Matheſeos Profeſſore *Lucaſiano*, & Societatis Regalis Sodali.

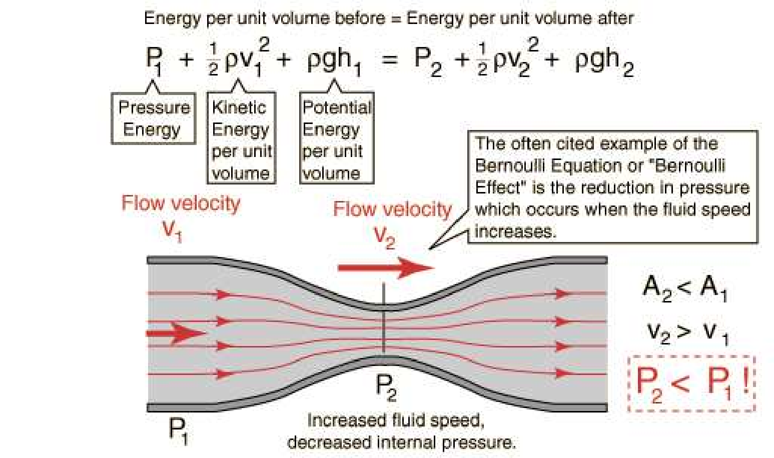
IMPRIMATUR
S. PEPYS, *Reg. Soc.* PRÆSES.
Julii 5. 1686.

LONDINI,
Juſſu *Societatis Regiæ* ac Typis *Joſephi Streater*. Proſtat apud plures Bibliopolas. *Anno* MDCLXXXVII.

A qualitative physical and mathematical understanding of fluid flow began - haltingly - only when Sir Issac Newton devoted Book II of his *Principia Mathematica* (1687) exclusively to the examination of fluid dynamics and fluid statics. Efforts to obtain a mathematical formulation of a fluid flow took shape during the century following the publication of *Principia Mathematica*.

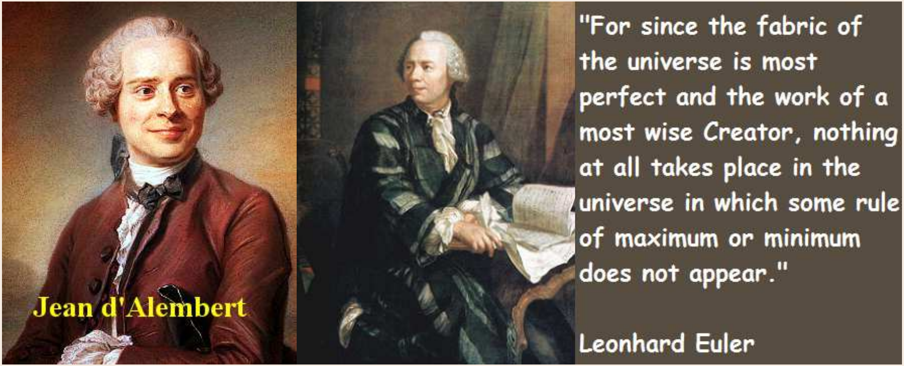
The Eighteenth Century Legends

Daniel Bernoulli (1700 - 1782)



The Eighteenth Century Legends

The Eighteenth Century: d’Alembert and Leonhard Euler



The Eighteenth Century Legends

Daniel Bernoulli, d'Alembert and Leonhard Euler

Among the three legends of the eighteenth century, Euler was the most instrumental in conceptualising the mathematical description of a fluid flow. He described flow in terms of spatially varying 3-D pressure and velocity fields and modelled the flow as a continuous collection of infinitesimally small fluid elements. By applying the basic principles of mass conservation and Newton's second law, Euler obtained two coupled, nonlinear partial differential equations involving the flow fields of pressure and velocity.

The Nineteenth Century: Complexities Begins

Journey from the Eighteenth Century to the Nineteenth Century

Although those Euler equations were an intellectual breakthrough in theoretical fluid dynamics, obtaining general solutions of them was quite another matter. Moreover, Euler did not account for the effect of friction acting on the motion of the fluid elements; i.e., he ignored viscosity. It was another hundred years before the Euler equations were modified to account for the effect of internal friction within a flow field. The resulting equations, a system of even more elaborate nonlinear partial differential equations now called the **Navier-Stokes equations***.

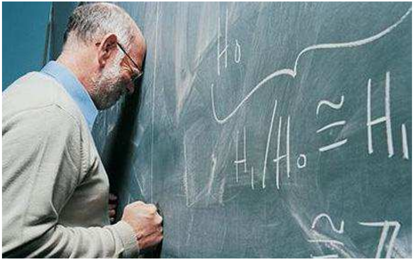
$$\overbrace{\rho\Big(\underbrace{\frac{\partial \mathbf{v}}{\partial t}}_{\substack{\text{Eulerian}\\ \text{acceleration}}} + \underbrace{\mathbf{v}\cdot\nabla\mathbf{v}}_{\text{Advection}}\Big)}^{\text{Inertia (per volume)}} = \overbrace{\underbrace{-\nabla p}_{\substack{\text{Pressure}\\ \text{gradient}}} + \underbrace{\mu\nabla^2\mathbf{v}}_{\text{Viscosity}}}^{\text{Divergence of stress}} + \underbrace{\mathbf{f}}_{\substack{\text{Other}\\ \text{body}\\ \text{forces}}}.$$

---

*These equations were first derived by Claude-Louis Navier in 1822, and then independently derived by George Stokes in 1845. To this day, those equations are the gold standard in the mathematical description of a fluid flow, and no one has yet obtained a general analytical solution of them.

The 20^{th} Century: Race between Theory and Inventions

Frustration due to inability in solving the Navier-Stokes Equations

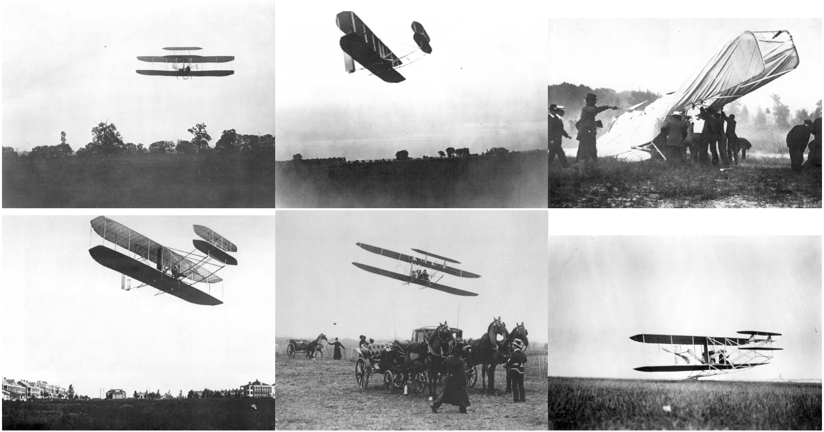


The inability to solve the Navier-Stokes equations for most practical flow problems was particularly frustrating to those investigators interested in calculating the frictional shear force on a surface immersed in a flow. This difficulty became acute at the beginning of the 20th century, with the invention of the first practical airplane by Orville and Wilbur Wright and with the subsequent need to calculate the lift and drag on airplanes.

The 20^{th} Century: Race between Theory and Inventions

“No invention waits for a theoretical explanation for long. As and when the right time comes, the inventions take place in due course.” —

Orville Wright and Wilbur Wright Brothers (17 December 1903)



Why am I telling all these stories here ????

Because the "Atmosphere" is a fluid, and hence the "Atmospheric Modelling" is essentially a topic dealing with the "Computational Fluid Dynamics"

The "Atmospheric Boundary Layer (ABL)":

The ABL is formed as a consequence of the interactions between the atmosphere (fluid) and the underlying surface (land or water).

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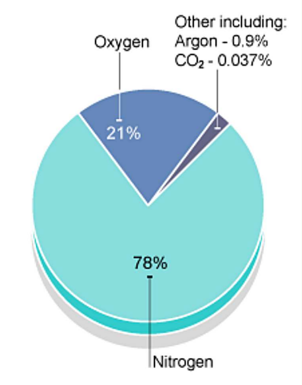
Composition of the Earth's Atmosphere

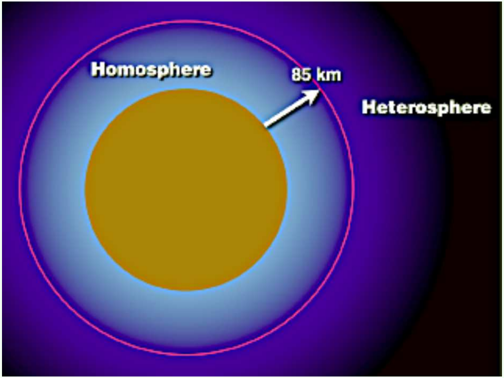
Different Gases of the Earth's Atmosphere



- **So-called "Permanent" Gases:**
  N_2, O_2, Ar and traces of other inert gases
- **Water (H_2O):**
  in all three of its phases (i.e., ice, liquid & vapour)
- **Variable gasesous constituent other than water:**
  CO_2, O_3, N_2O, CH_4
- **Aerosols:**
  solid & liquid particles suspended in air

Life is too Simple; Isn't it ???

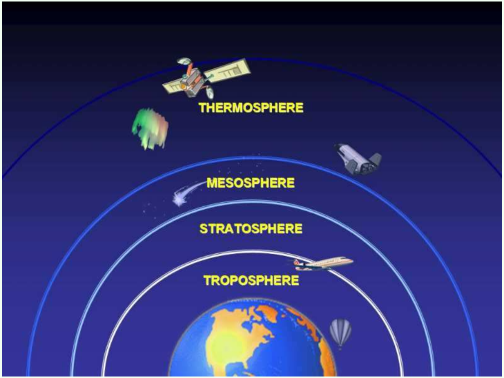
Vertical Layers of the Earth's Atmosphere



[Figure Courtesy: http://web.atmos.ucla.edu/]

I wish... "Life was simpler !!!"

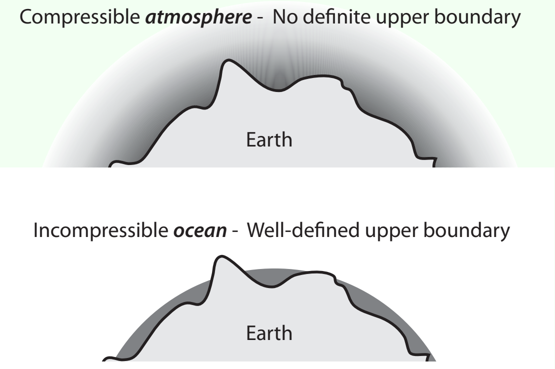
Vertical Layers of the Earth's Atmosphere



[Figure Courtesy: http://www.vtaide.com/png/atmosphere.htm]

Let us enjoy the "Complexity of Life"

Compressible Fluids and Incompressible Fluids



[Figure Courtesy: "A First Course in Atmospheric Thermodynamics", by: Grant W. Petty]

Earth's Atmosphere as a "Fluid"

Compressible Fluids and Incompressible Fluids

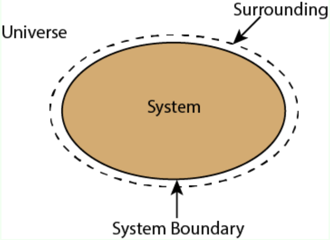
COMPRESSIBLE FLUIDS:

- every fluid that we encounter in our lives
- compressibility of a fluid is the reduction of volume in presence of external force

INCOMPRESSIBLE FLUIDS:

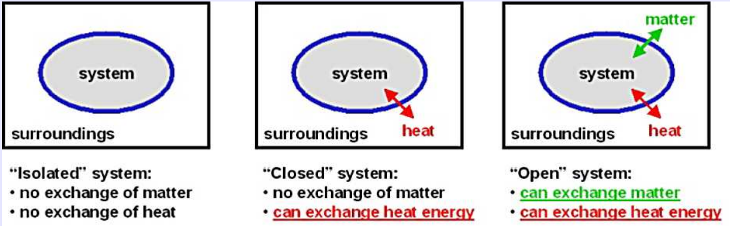
- hypothetical type of fluids (introduced for the convenience of calculations)
- it does not change the volume of the fluid due to external force

Thermodynamic Systems and Environment



- **THERMODYNAMIC SYSTEM**:
  ... which we are specifically interested in
- **ENVIRONMENT (UNIVERSE):**
  ... everything else other than the system

Different Types of Thermodynamic Systems



Weather and Climate Science

WEATHER AND CLIMATE

"Climate is what you expect, Weather is what you get."

- - - Robert A. Heinlein

A Precise Definition:

Weather reflects short-term conditions of the atmosphere while climate is the average daily weather for an extended period of time at a certain location.

"Weather is what the forecasters on the TV news predict each day. It is the mix of events that happens each day in our atmosphere. Weather is not the same everywhere. It may be hot and sunny in one part of the world, but freezing and snowy in another."

- - - NOAA Website

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Key Questions about the Weather:

1. **What controls the "Weather" ?**
2. **Understanding the "Weather" ??**
3. **Is "Weather" Predictable ??? - YES**

- Weather Predictions Techniques
- Meteorological Data: Availability & Usage
- True Representation of the Atmospheric State
- Gray areas in the Weather Prediction Science
- … … … … … …

Something from the History of “NWP”

For millennia people have tried to forecast the weather......!

- In 650 BC, the Babylonians predicted the weather from cloud patterns as well as astrology.
- In about 340 BC, Aristotle described weather patterns in Meteorologica.
- Later, Theophrastus compiled a book on weather forecasting, called the Book of Signs.
- Chinese weather prediction lore extends at least as far back as 300 BC.
- Ibn Wahshiyya’s Nabatean Agriculture discussed the weather forecasting of atmospheric changes and signs from the planetary astral alterations; signs of rain based on observation of the lunar phases; and weather forecasts based on the movement of winds.
- **No matter, how complicated the ’weather forecasting’ might be; It remained one of the most common and always attempted subjects by people in past....**

Ancient Techniques of Weather Prediction

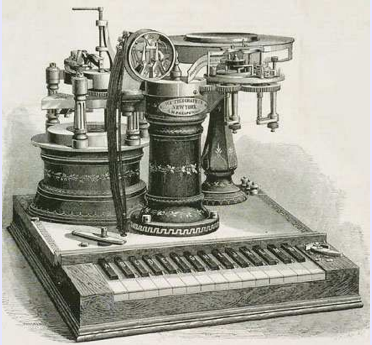
Folklore Forecast

Ancient weather forecasting methods usually relied on observed patterns of events, also termed pattern recognition. For example, it might be observed that if the sunset was particularly red, the following day often brought fair weather.

However, not all of these predictions prove reliable, and many of them have since been found not to stand up to rigorous statistical testing.

Ancient Techniques of Weather Prediction

Electric Telegraph


THE PHELPS ELECTRO-MOTOR PRINTING TELEGRAPH

With the invention of electric telegraph in 1835, the modern age of weather forecasting began. It allowed transformation of the state of weather at one place to other at a very high speed providing better clues on weather elsewhere ...

Before invention of electric telegraph, it was not possible to pass information on weather faster than a steam engine ....!

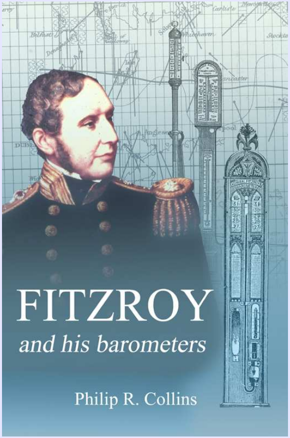
Ancient Techniques of Weather Prediction

Birth of Forecasting as a Science

The two men most credited with the birth of forecasting as a science were Francis Beaufort (remembered chiefly for the Beaufort scale) and Robert FitzRoy (developer of the Fitzroy barometer).

Beaufort Scale

Beaufort number	Wind Speed (mph)	Seaman's term		Effects on Land
0	Under 1	Calm		Calm; smoke rises vertically.
1	1-3	Light Air		Smoke drift indicates wind direction; vanes do not move.
2	4-7	Light Breeze		Wind felt on face; leaves rustle; vanes begin to move.
3	8-12	Gentle Breeze		Leaves, small twigs in constant motion; light flags extended.
4	13-18	Moderate Breeze		Dust, leaves and loose paper raised up; small branches move.
5	19-24	Fresh Breeze		Small trees begin to sway.
6	25-31	Strong Breeze		Large branches of trees in motion; whistling heard in wires.
7	32-38	Moderate Gale		Whole trees in motion; resistance felt in walking against the wind.
8	39-46	Fresh Gale		Twigs and small branches broken off trees.
9	47-54	Strong Gale		Slight structural damage occurs; slate blown from roofs.
10	55-63	Whole Gale		Seldom experienced on land; trees broken; structural damage occurs.
11	64-72	Storm		Very rarely experienced on land; usually with widespread damage.
12	73 or higher	Hurricane Force		Violence and destruction.



Ancient Techniques of Weather Prediction

Weather Forecasting: Some Ancient Techniques

Persistence	:	It greatly relies upon today's conditions to forecast the conditions tomorrow
Climatology	:	the long-term average weather conditions are used to predict the weather for a given day
Trend forecast	:	the weather will change, assuming that weather changing pattern will continue at present rate
Analog forecasts	:	basic premise: history repeats itself, so find similar events in the past and see what happened next...
Numerical forecasting	:	Atmospheric Model + Computers
Ensemble forecasting	:	Set of Models with scientifically significant ensembling

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Weather Predicions: Meteorologist's View

Weather Predictions: Five Basic Steps of a Meteorologist

(1) Observations

(2) Collection and Transmission of Weather Data

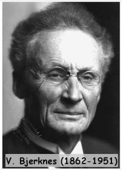
(3) Plotting of Weather Data

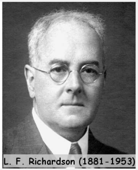
(4) Analysis of Weather Maps, Satellite and Radar Imagery and Other Data

(5) Formulation of the Forecast

Numerical Weather Predictions: A New Science Stream

Evolution of “Numerical Weather Prediction” as a New Science Stream



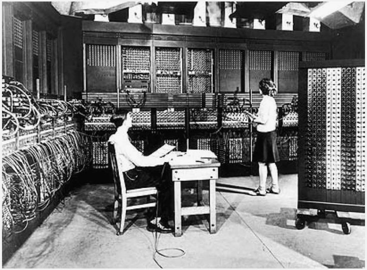


Abbe: recognized the field of “meteorology” as application of hydrodynamics and thermodynamics to atmosphere.

Bjerknes: possibility of weather prediction in a scientific manner as an initial value problem

Richardson: devised the mathematical formulation through finite difference schemes for NWP

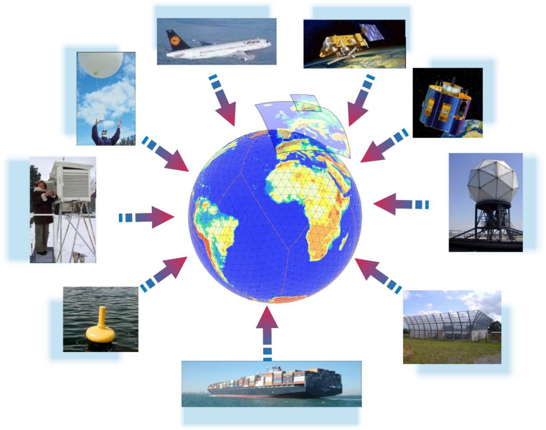
First weather forecasts for +24 hours through computers in 1950 by J. Charney and J. Neumann



The Electronic Numerical Integrator and Computer (ENIAC)
Charney, J. (1951), American Meteorological Society.

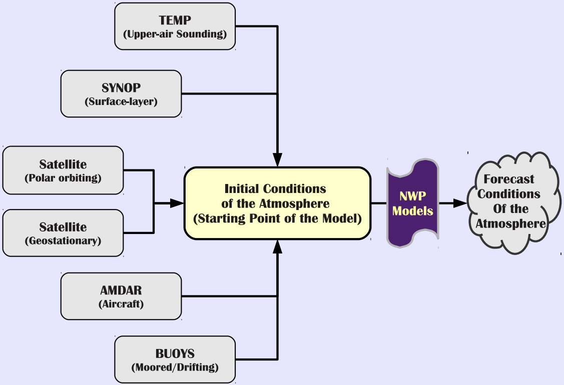
Numerical Weather Predictions: A New Science Stream

OBSERVATIONS $\Longrightarrow$ Initial Conditions of the Atmosphere



Numerical Weather Predictions: A New Science Stream

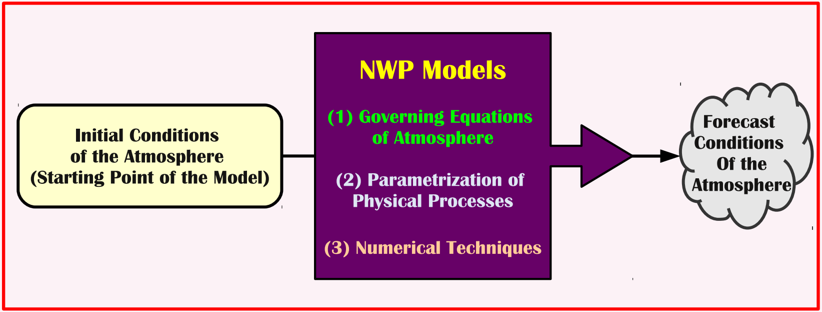
Based on the initial conditions, NWP models generate forecasts



But, What is exactly inside this NWP Model (Black Box ???)

NWP Models: Inside the Black-Box

Numerical Weather Prediction Models

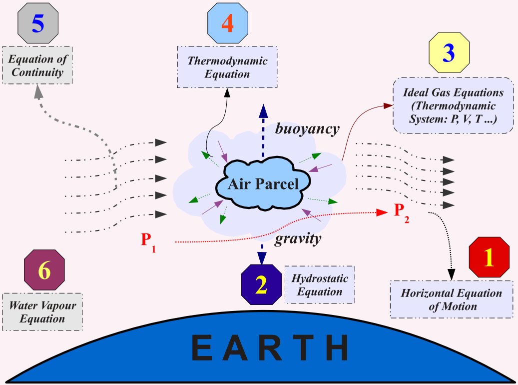


While different NWP models vary from each other either due to their differences in - (i) initial conditions; (ii) parametrization or (iii) numerical techniques; the Governing Equations of the Atmosphere remain same for all the models.

Different Atmospheric Processes: A Schematic

Governing Equations of the Atmosphere: A Schematic

Forecast Variables: u, v, w, T, q, **and** z



All the governing equations of atmosphere are solved at grid points.

Governing Equations of the Atmosphere

Governing Equations of the Atmosphere: A Simplified Approach

Simplest Forecast Equation

Let us define the rate of change of an atmospheric variable A with respect to time (t) in a simplest mathematical form:

$$\frac{\triangle A}{\triangle t} = F(A)$$

In NWP, future values of meteorological variables are solved by finding their initial values and then adding the physical forcing that acts on the variables over the time period of the forecast. This can be stated as:

$$A^{forecast} = A^{initial} + F(A).\triangle t$$

- -

$\triangle A$ = the change in a forecast variable at a particular point in space,
$\triangle t$ = the change in time (how far into the future we are forecasting),
$F(A)$ stands for the combination of all of the kinds of forcing that can occur.

Governing Equations of the Atmosphere

Governing Equations of the Atmosphere: A Simplified Approach

Wind Forecast Equation (Prognostic Equation)

$$\frac{\partial u}{\partial t} = - \; u\frac{\partial u}{\partial x} - v\frac{\partial u}{\partial y} \; - \; w\frac{\partial u}{\partial p} + fv - g\frac{\partial z}{\partial x} + F_x$$

$$\frac{\partial v}{\partial t} = - \; u\frac{\partial v}{\partial x} - v\frac{\partial v}{\partial y} \; - \; w\frac{\partial v}{\partial p} + fu - g\frac{\partial z}{\partial y} + F_y$$

- -

Physical Interpretation:

Change in horizontal winds with respect to the time =

horizontal advection + vertical advection + geostrophic balance + surface friction/turbulence

Governing Equations of the Atmosphere

Governing Equations of the Atmosphere: A Simplified Approach

Continuity Equation (Diagnostic Equation)

$$\boxed{\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y}} + \boxed{\frac{\partial w}{\partial p}} = 0$$

- -

Physical Interpretation:

Conservation in mass is maintained as:

horizontal advection + vertical advection

The continuity equation is used to calculate vertical motion in hydrostatic models.

However, non-hydrostatic models do not use the continuity equation directly to calculate vertical motion. Rather, they use a combination of horizontal divergence and buoyancy to determine both vertical motions and vertical accelerations.

Governing Equations of the Atmosphere

Governing Equations of the Atmosphere: A Simplified Approach

Temperature Forecast Equation (Prognostic Equation)

$$\frac{\partial T}{\partial t} = - \left(u\frac{\partial T}{\partial x} - v\frac{\partial T}{\partial y} \right) - w\left(\frac{\partial T}{\partial p} - \frac{RT}{C_p p}\right) + \frac{H}{C_p}$$

- -

Physical Interpretation:

Change in Temperature with respect to time =

horizontal advection of temperature

\+ **difference between vertical temperature advection and adiabatic process**

\+ **Other processes, i.e., radiation, mixing and condensation**

Governing Equations of the Atmosphere

Governing Equations of the Atmosphere: A Simplified Approach

Moisture Forecast Equation (Prognostic Equation)

$$\frac{\partial q}{\partial t} = - \; u\frac{\partial q}{\partial x} - v\frac{\partial q}{\partial y} \; - \; w\frac{\partial q}{\partial p} + E - P$$

- -

Physical Interpretation:

Change in Moisture with respect to time =

horizontal advection of moisture

+ vertical advection of moisture

+ evaporation and sublimation

+ condensation and precipitation

Governing Equations of the Atmosphere

Governing Equations of the Atmosphere: A Simplified Approach

Hydrostatic or Vertical Momentum Equation (Diagnostic Equation)

$$\frac{\partial z}{\partial p} = - \frac{RT}{pg}$$

- -

Physical Interpretation:

difference in height between upper and lower isobaric surface =

mean temperature within a layer

The hydrostatic equation preserves stability within the forecast model and is used to calculate the height field necessary for determining geostrophic balance in the wind forecast equations. This diagnostic equation links the mean temperature in a layer of the model to the difference in height between the upper and lower isobaric surfaces serving as the top and bottom of the layer.
Updated temperatures obtained from the temperature forecast equation are used here to calculate heights, which are then used in the wind forecast equations.

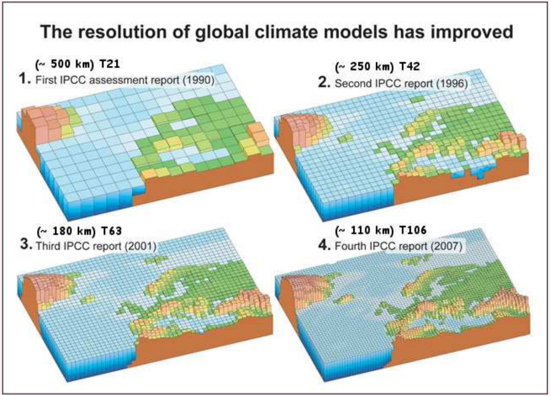
Global and Regional NWP Models

Global Models and Regional NWP Models: Current Scenario

Global Models: Coarse Grid-resolution and associated larger time-steps
Regional NWP Models: Fine Grid-resolution and shorter time-steps

Global and Regional NWP Models

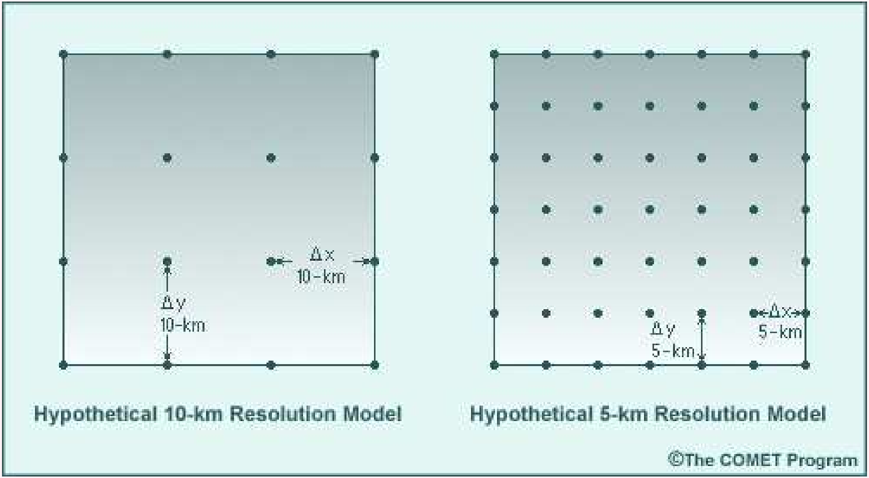
Global Models and Regional NWP Models: Current Scenario



As of now (2014), the grid-resolutions of Global Models have come down to as low as 0.20 ($\sim$ 20 km)

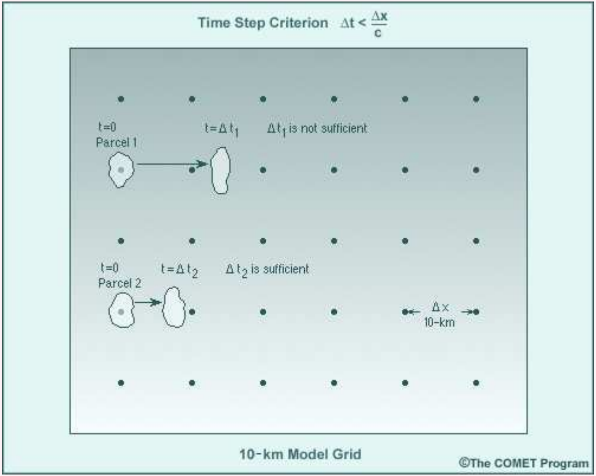
NWP Models: Future Scenario

Impact of Reduction in Grid-resolution of Global Models



NWP Models: Future Scenario

Impact of Reduction in Grid-resolution of Global Models



NWP Models: Future Scenario

Impact of Reduction in Grid-resolution of Global Models

- **Space-crunch in data archival ⇒ Optimum domains in regional NWP models**
- **Compulsion in reduction of grid-size resolutions in regional NWP models**
- **Special emphasis on "local data assimilation" for improvements in forecasts**
- **Focused attention on proper representation of sub-grid scale processes**
- **Migration from hydrostatic to non-hydrostatic atmospheric models**

Hydrostatic and Non-Hydrostatic Models

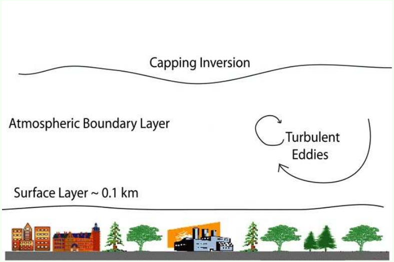
Comparison between Hydrostatic and Non-Hydrostatic Models

	Hydrostatic	Non-hydrostatic
Characteristics	prediction of vertical motion (diagnostic approach)	prediction of vertical motion (direct forecasting)
	good for synoptic-scale phenomena	good for micro-scale phenomena
Advantages	quick for forecasting (operational usage)	can account for physical processes associated with vertical velocities
	assumptions valid for synoptic and sub-synoptic scale	capable of predicting convection and mountain-waves
Disadvantages	cannot predict vertical accelerations	excessive time consumption in forecast
	cannot predict small-scale processes	more dependence on boundary conditions

Back to “Hydrostatic and Non-Hydrostatic Models”

Parametrization of Surface-layer Processes

ABL processes (sub-grid scale in nature) are treated through two distinct parametrization schemes in the NWP models :



- **Surface-layer Parametrization Scheme:**

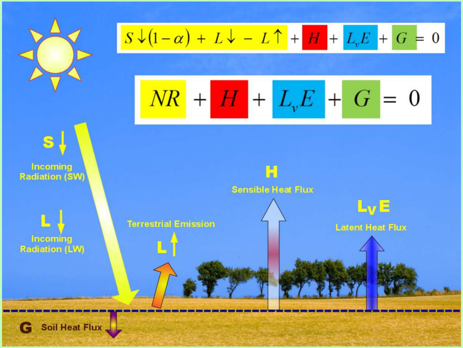
  It deals with the exchange of momentum, heat and moisture between the Earth's surface and the atmosphere above

- **ABL (or PBL) Parametrization Scheme:**

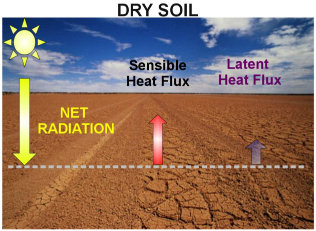
  It controls the diffusion of above mentioned quantities within the ABL and its interaction with the free troposphere above

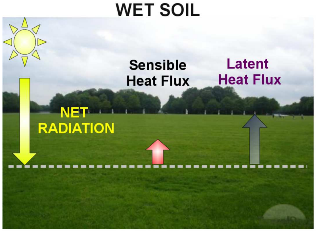
Parametrization of Surface-layer Processes

A Simplified Surface Energy Budget Schematic



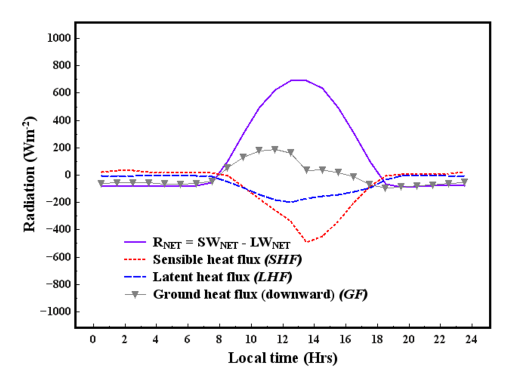
The "surface-layer parametrization schemes" in NWP models deal with the quantification of energy budget through estimation of turbulent fluxes of heat, moisture and momentum at surface.





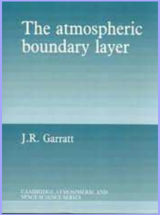
Parametrization of Surface-layer Processes

HRM simulations of various components of simplified surface energy budget over Thiruvananthapuram for a clear-sky day

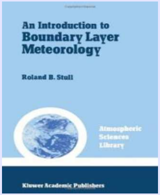


▸ Back to Simplified Surface Energy Budget

Text-Book definitions of the “ABL”



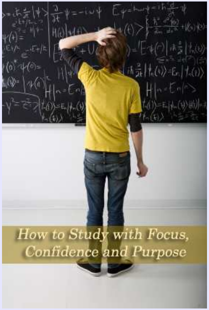
... ... “ the layer of air directly above the Earth’s surface in which the effects of the surface (friction, heating and cooling) are felt directly on time scales less than a day, and in which significant fluxes of momentum, heat or matter are carried by turbulent motions on a scale of the order of the depth of the boundary layer or less. ” ... ...

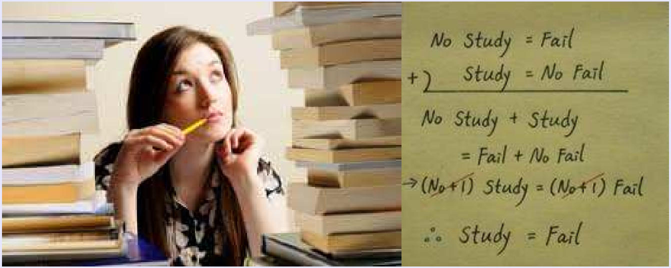


... ... “ that part of the troposphere that is directly influenced by the presence of the earth’s surface, and responds to surface forcings with a timescale of about an hour or less. These forcings include frictional drag, evaporation and transpiration, heat transfer, pollutant emission, and terrain induced flow modification. ” ... ...

What's the Motivation for ABL Studies ???

Why should I study this "ABL" ???





Why to study this “ABL” ???

Significance of the “ABL” Studies

1. Atmospheric Energetics

- The primary energy source for the whole atmosphere is solar radiation, which for most part is absorbed at the ground and transmitted to the rest of the atmosphere through boundary-layer processes.
- About 90% of the net radiation absorbed by oceans cause evaporation, amounting to the evaporation of about 1 metre of water per year over the earth’s ocean area.
- About 50% of the atmospheric kinetic energy is dissipated in the ABL. The latent heat stored in water vapour accounts for about 80% of the fuel that drives atmospheric motion.

Why to study this “ABL” ... ???

Significance of the “ABL” Studies

2. Weather and Safety

- Daily weather forecasts of dew, frost, and other meteorological features are actually the boundary-layer forecasts
- Aviation, shipping, and other navigation activities are directly linked with the boundary-layer processes
- Thunderstorm and hurricane evolution are directly tied to the inflow of moist boundary-layer air
- Turbulence and gustiness affects architecture in the design of structures
- Pollution is trapped in the boundary-layer
- Fog occurs within the boundary-layer

Why to study this “ABL” ... ???

Significance of the “ABL” Studies

3. ABL as an Energy Hub

- Wind turbines extract energy from the boundary-layer winds
- Wind stress on the sea surface is the primary energy source for ocean currents
- Turbulent transport and advection in the boundary-layer move water and oxygen to and from immobile life forms like plants

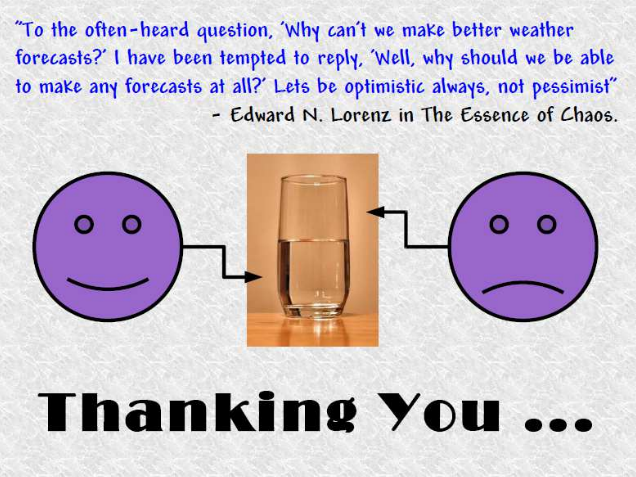
4. Relevance and Importance of ABL processes in NWP

5. ABL Processes and their impact on the Clouds

6. Climate Change and its final impacts on the ABL

... ...

My Sincere Thanks to Each One of You



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