Nicholson

- albedo – 2 questions.
- surface energy balance + net radiation at TOA
- surface heat balance – 2 questions. ✓
- 〃 .
- 4 major eqs of heat
- main stationary waves
- General atmospheric circulation – 4 major factors + characteristics.
- 〃 〃 〃 in N.H + S.H. ✓
- hydrology eq.
- water storage
- Climate types w.r.t. rainfall ✓
- land surface in the GCM
- atmospheric energy cycle. ✓
- Equatorial westerlies et. al.

* albedo

5105

MET? (Global Climate System): Nicholson (1 hour, 1996, 1997) **

- Question

a. Define albedo verbally and mathematically.

✓b. Explain how it depends on the physical and chemical properties of the reflecting surface, giving specific examples of various natural surfaces.

c. For any surface at a given time and location, what factors (beside its own characteristics) determine its albedo.

based on In's answer (he got 8.5/10)

Sol)

a) Albedo is the ratio of reflected to incident solar radiation, integrated over all wavelengths.

$$\boxed{A = \frac{\int_0^\infty r_\lambda \cdot m_\lambda \, d\lambda}{I_0}}$$

where r_λ : monochrometric reflectivity

m_λ : (" reflected solar radiation) → No!

└→ incident flux.

I_0 : total incident solar flux

b) Since each sfc can be regarded as a reflection plane, albedo thus depends on the number, and shape, and size and slope (w.r.t. the incident flux) of the reflection planes. For example, the vegetation type, shape of the leaves of vegetation. For the chemical properties: the chemical ingredients of the reflecting sfc can cause different efficiency of the absorption, as well as the reflection for different wave length. For example the chlorophyll in the vegetation leaves determines the reflection efficiency of different wavelengths (as we see the different colors)

- examples : physical → shape of vegetations (leaves or cylender ↙?)
  chemical → spectral reflection of vegetation due to chlorophyll.

c) Factors include :

- Solar elevation
- time of day
- season of year
- latitude
- State of sky
- Slope of the reflection surface
- ratio of diffused to incident flux. ✓

(c) Solar elevation, time of day, season, latitude, state of sky, slope of sfc ratio of diffuse to direct radiation.

---

a) Albedo ≡ ratio of reflected to incident solar radiation integrated over all solar wavelengths

$$A = \frac{\int_0^\infty r_\lambda m_\lambda \, d\lambda}{I_0}$$

r_λ – monochromatic reflection

m_λ – " incident flux

I_0 – total incident flux

b)

- Physical : Each physical surface is a reflection plane, so total reflection depends on number + inclination (w.r.t. incident flux) + shape + size of the reflecting sfc
- Chemical : Chemicals differ w.r.t. the efficiency of absorption of solar wavelengths

4

* albedo

$$A = \frac{\int_0^\infty r_\lambda m_\lambda d\lambda}{I_0}$$

✓ MET$\overset{5105}{?}$: Nicholson (30 min) *

- Write an equation defining surface albedo. Describe its dependency on solar elevation angle and how it might be affected by a) surface geometry and b) the ratio of diffuse to direct radiation. Describe and compare its wavelength dependency for the following types of surfaces: bare soil, water, vegetation, snow. ?

see the previous question, and others

* Surface energy balance + net radiation at TOA

MET? : Nicholson (?, 1996) *

- Question

a. Give the surface energy balance equation in a form that explicitly includes the surface albedo. For each term, explain what characteristics of the surface of atmosphere are the min determinants. Describe how you would expect each term to differ for the following types of climate: tropical desert with low cloudiness; mid-latitude forest; low latitude ocean with year-round cloudiness. Include the seasonal variation of the terms in your answer.

✓ b. Give the formula for net radiation at the top of the atmosphere, indicate what determines each term, and describe where over the earth you would expect particularly large or particularly small values of top-of-atmosphere net radiation and why.

a.

$$\star\ R_{SW}\downarrow(1-a_s) - R_{LW}\uparrow + R_{LW}\downarrow = \underbrace{LE}_{\text{latent heat flux (evaporation)}} + \underbrace{\overset{\text{to air}}{S} + \overset{\text{to ground}}{G}}_{\text{sensible heat flux}}$$

- Tropical desert w/ little cloudiness :
  - a_s : high but $R_{SW}\downarrow$ also high
  - $R_{LW}\uparrow$: high
  - $R_{LW}\downarrow$: low because of little cloudiness + dry air over desert. (dry air → little H_2O vapor)
  - LE : low
  - S : high
  - G : low → little surface moisture.
  - → seasonal variation is low for all of these.
- Mid-lat. forest :
  - a_s : low with seasonal variation if deciduous trees (→ trees with leaves)
  - $R_{SW}\downarrow$: relatively low and large seasonal change
  - $R_{LW}\uparrow$: " " , long seasonal change deciduous
  - $R_{LW}\downarrow$: " high because of clouds, H_2O vapor, seasonal variation if cloud + precip and H_2O vapor change.
  - LE : high during warm season, low during winter unless moist soil.
  - S+G : low since T of forest is relatively low ; long seasonal variation.
- low latitude ocean w/ year round cloudiness
  - a_s : low
  - $R_{SW}\downarrow$: low to moderate because of clouds
  - $R_{LW}\uparrow$: low because of low T.
  - $R_{LW}\downarrow$: high because of cloud
  - LE : high
  - S : low because of low T
  - * G : relatively high due to convection.
  - } little seasonal variation.

Type of sfc	Specific heat	Albedo
bare soil	~0.2	0.1 → 0.4
Ice	0.5	0.3
water	1.0	0.06
deciduous forest	~	0.1 → 0.2
grass/crop	~	0.15 → 0.25

* Surface heat balance

MET?: Nicholson (30 min)

- Write a complete and detailed equation for surface heat balance which included surface albedo and sensible heat to the subsurface explicitly and two terms each for shortwave and longwave radiation (plus remaining terms).

see the previous or the next questions

$$R_{SW}\downarrow(1-a_S)-R_{LW}\uparrow+R_{LW}\downarrow=LE+S+G$$

1/2

* Surface heat balance

MET?: Nicholson (30 min) *

- Write a complete equation for the surface heat balance. Describe the factors which determine the magnitude of each term. Give a qualitative discussion of the comparative magnitude of all terms for a mid-latitude ocean surface and a low-latitude desert. In this discussion, describe in detail subsurface processes and how they influence the surface heat balance.

* * Surface energy balance ← general note

- Surface energy balance eq

$$R_{net} = R_{sw\downarrow}(1-a_s) + R_{lw\downarrow} - R_{lw\uparrow} = LE + S$$

R_{net} = the net amount of radiant energy available.
$R_{sw\downarrow}$ = solar radiation (SW) reaching the earth sfc.
a_s = sfc albedo
$R_{lw\downarrow}$ = longwave radiation emitted earthward from clouds + atmosphere.
$R_{lw\uparrow}$ = " " " spaceward from earth sfc.
LE = latent heating
S = sensible heat transfer through conduction (G) or convection (H)

- Albedo : The albedo is the ratio of reflected radiation to incident solar radiation for all wavelengths

$$a = \int_0^{\infty} \underbrace{r_\lambda}_{\text{monochromatic reflectivity}} \underbrace{I_\lambda d\lambda}_{\text{monochromatic incident flux}} \Big/ \underbrace{I_0}_{\text{total incident radiant flux}}$$

Albedo is a very complex concept. We can estimate it from satellite.

- Physical reasons for variability of Albedo.
  - composition of incident radiant flux ⇒ the wavelength.
  - geometry of sfc : the geometry and type of the sfc determine the magnitude of albedo.
  - in presence of vegetation

	albedo
grass	15-25%
forest-mid-lat.	10-20%
forest-tropics	7-15%

  - Short wave radiation trapping in the leaves in vegetation canopy

  - the short wave radiation penetration through a layer of vegetation depends on the distribution of the foliage.
  - wet/dry sfc
    → wet sfc albedo is 10% ; dry sfc is 15-25%
    The type of soil for a dry sfc determines the magnitude of the albedo. In bare soil and desert, there is high albedo if we also consider OLR from the desert (a cloudless area). There is a net loss of radiation so the subsidence of air in the high pressure region increases. The adiabatic warming of subsidence balances the radiative cooling. The net radiation at the sfc is low with high albedo.
  - The slope of the sfc determines the magnitude of the albedo

* Sensible heat flux

At a given point at the sfc of the earth, the net radiative heat gain is equal to the net heat loss

$$R_{net} = LE + S$$

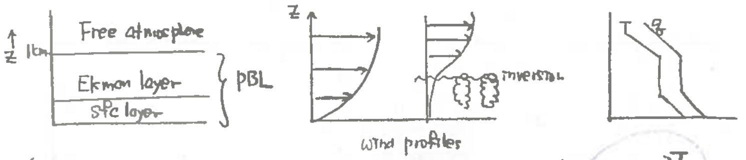
where R_{net} = the heat gain at sfc due to net radiation
LE+S = the heat loss from the sfc due to latent heat (evaporation-condensation) and the sensible heat.

The sensible heat S from the sfc includes two processes

$$S = G + H$$

H → sensible heat flux due to convection above the sfc into air
G → sensible heat flux due to conduction between sfc + soil below.

The loss due to latent heat LE occurs at a higher level in the atmosphere than the loss due to sensible heat fluxes. As the sensible heat flux is a near surface process, surface geometry, temperature gradient, wind momentums in the PBL i important in determining the sensible heat flux. The sensible heat fluxes depend on the thermodynamic + dynamic structure of the PBL.



wind profiles

The rate of heat flux along the temperature gradient is given by $S = K\frac{\partial T}{\partial z}$ → exchange coefficient

Time rate change in flux $\frac{\partial S}{\partial z} = -C_v\frac{\partial T}{\partial t}$ → C_v: heat capacity.

why

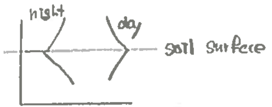
Diffusion eq : $\frac{dT}{dt} = \frac{K}{C_v}\frac{\partial^2 T}{\partial z^2}$

So the rate of heat flux depends on the temperature gradient between the sfc and atmosphere just above the sfc. The sensible heat flux can also be describe using similarity theory

✓ $S = C_p \rho C_H \overline{V_a}(\overline{T_s} - \overline{T_a})$

C_p → specific heat
$\overline{T_s}$ → mean T_{sfc}
$\overline{T_a}$ → temp at top of sfc layer.

The temperature varies with height in both the atmosphere and soil with diurnal cycle



Air has a higher heat capacity (C_v) than ground so the temperature fluxes go from ground to the air.

In vegetation covered areas mixing takes place and sensible heat flux is high
→ low thermal capacity.

In a dry sfc like a desert, during the day soil temp is high and sensible hea transfer occurs through convection ⇒ transfer from soil to air.

Wet surfaces, such as water, have a higher heat capacity so the rate of flux from wet sfc is less than that of dry sfc but conductivity of heat throug wet soil is high.

- OLR

OLR ⇒ $R_{lw\uparrow}$ from the sfc can be estimated using Stefan-Boltzmann law

$$\Rightarrow R_{lw\uparrow} = \sigma_E T^4$$

σ_E → Stefan Boltzmann constant.

We can see from this eq that $R_{lw\uparrow}$ will be much greater over a dry, high temperature sfc (desert) than over a wet sfc

In forested regions we can have two levels of $R_{LW}\uparrow$

→ the sfc + top of forest canopy.

* * *

Recall surface balance energy eq.

$$LE + S = R_{net} = R_{SW}\downarrow(1-a_s) + R_{LW}\downarrow - R_{LW}\uparrow$$

- $R_{SW}\downarrow$ → short wave radiation at the sfc. The only important source of energy for the earth atmosphere is solar radiation. Variations in the input of SW will have an impact on climate.
- We used to take the mean of solar energy at the top of the atmosphere to be the solar radiation constant. In reality, the SW intercepted by the top of the earth's atmosphere is not constant. The solar radiation at the top of the atmosphere varies according to
  - ① revolution → shape of earth orbit + distance from the sun
  - ② tilt of earth axis → 23½° on a seasonal mean timescale
  - ③ rotation rate of the earth → length of day.

  We use 1395 W/m², 1370 W/m², 1353 W/m² for the solar "constant".

  Some research suggest a link between the solar constant, sunspots + droughts but this has yet to be proven. Regardless, the latitudinal variation of solar energy has a significant impact on the NS temperature gradient which drives much of what we call weather.
- Surface albedo (a)

  ↳ ratio of reflected to incident solar radiation at the sfc integrated over all wavelengths.

$$a = \frac{\int_0^\infty r_\lambda m_\lambda d\lambda}{I_0}$$

r_λ → monochromatic reflection

m_λ → " incident flux

I_0 → total incident SW radiation

There are many factors which determine the magnitude of albedo.
These factors include : geometric shape of the sfc, type of sfc, slope of sfc.

- Over desert areas the albedo is high (~40%) The deserts are therefore a region of net radiative cooling (high albedo + high $R_{LW}\uparrow$ due to high sfc temps). To compensate for the negative net radiation balance, deserts are regions of strong subsidence. The adiabatic warming of subsiding air balances the radiative cooling of air.
- Over a mid-lat. oceanic region the albedo is low for two reasons
  - ① albedo over water is generally low (10%) but does vary with zenith angle
  - ② the degree (angle) between the incident solar beam and the sfc of the water determines the magnitude of the albedo. The sea state (waves) also affect the albedo.
- Sensible heat

  → the heat balance at a particular point of the earth sfc satisfies the eq. $R_{net} = LE + S$

  sensible heat can be broken into that due to conduction G + that due to convection H ⇒ $S = G + H$

  H ↳ between sfc + air

  G ↳ between sfc + soil below.

  Over a desert area the sensible heat flux can be described as follows. During the day the sfc is warm so there is a transfer of T from the sfc to the air since the heat capacity of air is higher than that of the ground. The rate of sensible heat flux $S = K\frac{\partial T}{\partial z}$ and the vertical gradient of sensible heat flux $\frac{\partial S}{\partial z} = -C_v\frac{\partial^2 T}{\partial z^2}$. The rate of sensible heat flux is also dependent on the wind profile in the PBL. Over the desert if the soil is bare there will not be much turbulence in the flow. The composition of the soil will determine the conductivity for sensible heat flux down into ground.

  Over mid-lat. ocean

  ↳ Water has a high heat capacity. So while sensible heat transfer takes place it is much less than over the desert. It depends, in part, on the air mass over the ocean (colder or warmer than water) The wind profile is smooth over oceans unless there are high waves.
- Latent heat term is high. The temperature + moisture of the air determine the effect of this term. Latent heat transfer penetrates further up into the atmosphere than sensible heat flux.
- LW radiation ⇒ $LW\uparrow = \sigma_E T^4$ so
  - → desert emit high $LW\uparrow$
  - → ocean " low $LW\uparrow$

* Surface heat balance

MET?: Nicholson (30 min)

- Describe how each term is influenced by the presence/absence of vegetation and by dry vs. wet surface conditions. Be sure to include the imports of wind/momentum and stability in making your assessment. Give, where appropriate, quantitative estimates of parameters such as albedo, roughness or thermal characteristics.

* See the previous question.

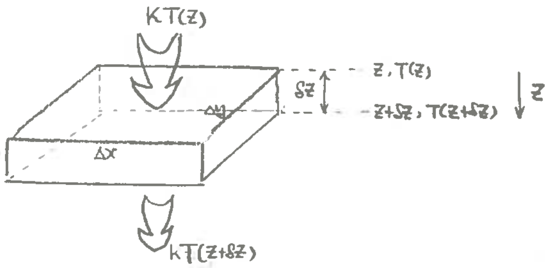
★ 4 major eqs of heat.

MET5105 (Global Climate System): Nicholson (45-60 min, 1997, 1998) ** W/m²

- Starting with the concept of a temperature gradient, derive the four major equations of the classical theory of the flow of heat, i.e., those for heat flux S, flux gradient $\partial S / \partial Z$, temperature change dT / dt, and flux change dS / dt. Define thermal conductivity, heat capacity, thermal diffusivity, and specific heat verbally. Relate this theory to the concepts of penetration depth of the annual or diurnal temperature wave, time lag of temperature with depth, magnitude of temperature at a given depth, and temperature gradient in ground.

Based on In's answer (He got 10/10)

Sol)



① Consider a cubic as above, heat flux is S

as conservation of heat energy

★ $S\Delta x\Delta y\Delta Z = KT(Z)\Delta x\Delta y - KT(Z+\delta Z)\Delta x\Delta y$ (unit = W·m)

express : $T(Z+\delta Z) = T(Z) + \frac{dT}{dZ}\cdot\delta Z$

we have $\boxed{S = -K\frac{dT}{dZ}}$ ——— (1)

Here S is the mean heat flux for depth δZ.

where $\delta Z \longrightarrow 0$ $S = S(Z)$

✓ K : thermal conductivity.

② Consider the same cubic, letting C_v be the heat capacity of soil.

Conservation of heat energy requires :

★ $S(Z)\Delta x\Delta y\,\delta t - S(Z+\delta Z)\Delta x\Delta y\,\delta t = C_v\Delta x\Delta y\delta Z\cdot\delta T$ (unit = J)

where, δT is the temperature change in time δt.

Rearrange the two sides of the eq.

$$\frac{S(Z)-S(Z+\delta Z)}{\delta Z} = C_v\frac{\delta T}{\delta t}$$

as $\delta Z \longrightarrow 0$, $\delta t \longrightarrow 0$, we have

$$\boxed{\frac{\partial S}{\partial Z} = -C_v\frac{dT}{dt}} \text{ ——— (2)}$$

In the following, we consider the parameter as constants, i.e.,

C_v = const.

K = 〃

③ $\therefore \frac{dT}{dt} \overset{eq(2)}{=\!=} -\frac{1}{C_v}\frac{\partial S}{\partial Z} \overset{eq(1)}{=\!=} -\frac{1}{C_v}\frac{d}{dZ}\left(-K\frac{dT}{dZ}\right)$

define : thermal diffusivity $\boxed{\alpha = \frac{K}{C_v}}$

$$\therefore \boxed{\frac{dT}{dt} = \alpha\frac{d^2T}{dZ^2}} \text{ ——— (3)}$$

④ $\frac{dS}{dt} \overset{eq.(1)}{=\!=} \frac{d}{dt}\left(-K\frac{dT}{dZ}\right) = -K\frac{d}{dZ}\left(\frac{dT}{dt}\right) \overset{eq(2)}{=} -K\frac{d}{dZ}\left(-\frac{1}{C_v}\frac{dS}{dZ}\right) = \alpha\frac{d^2S}{dZ^2}$

$$\therefore \boxed{\frac{dS}{dt} = \alpha\frac{d^2S}{dZ^2}} \text{ ——— (4)}$$

⑤ K : thermal conductivity, is the ability of media (soil) to transfor heat. It is defined as the amount of heat in unit time flowing through a unit cross section (1 cm²), in response to temperature gradient of 1°C/1 cm soil

C_v : heat capacity; the amount of heat required to raise a unit volume (1 cm³) of soil by 1 degree centigrade.

C_g : specific heat : the amount of heat required to raise a unit mass (1g) soil by 1 degree centigrade.

$\boxed{C_g = C_v/\rho}$, ρ is the density of soil

α : thermal diffusivity, defined as $\alpha = K/C_v$

It determines the temperature wave in the soil.

Since thermal diffusivity of the soil is small, temperature change with depth in the soil appears to be wave penetrating through the soil, with the magnitude of oscillation great on the surface, diminishing with depth into the lower depth

Let P be the period of the temperature oscillation, then :

- time lag of maximum or minimum temperature amplitude at depth Z_1 and Z_2 can be expressed as :

✓ $\boxed{t_1 - t_2 = \frac{Z_2 - Z_1}{2}\left(\frac{P}{\alpha\pi}\right)^{1/2}}$ ★★

- Range of temperature change at depth Z.

R_Z expressed in terms of the range at sfc R_S is

✓ $\boxed{R_Z = R_S e^{-Z\left(\frac{\pi}{\alpha P}\right)^{1/2}}}$ ★★

using, at daytime or warm season, temperature is maximum at sfc, decrea with depth. At night or winter season, this is reversed.

※ Units (in SI units)

$K = \frac{J}{m\,s\,°C}$: thermal conductivity

$C_g = \frac{J}{kg\,°C}$: specific heat ; $C_v = \frac{J}{\cancel{kg}\,°C}\frac{\cancel{kg}}{m^3}$ heat capacity

$\alpha = \frac{m^2}{s} \longleftarrow \frac{K}{C_v} = \frac{J/m\,s\,°C}{J/m^3\,°C} = m^2/s$

* main stationary waves

MET5135 (Dynamic Climatology): Nicholson (1 hour, 1997,1998) *

- Describe the main stationary waves in the northern and southern hemispheres in winter and in summer. Consider both surface and upper levels. Indicate main forcing mechanisms in each case and reasons for concluding that these are the forcing mechanisms.

based on In's answer (He got 10/10)

Sol)

① In the northern winter, 3-wave aloft with troughs located east of mountains (Alps, Himalayas and Andes), showing the orographic forcings. In the northern winter surface, there is 2-wave configuration, with lows over the oceans and highs over Asia and North America continents, showing the thermal forcing

② Northern summer, 3-wave on surface and aloft, with troughs positioned east of the mountains, presents the orographic forcing.

③ In the southern winter, there is one-wave on surface and aloft, showing the thermal and orographic forcing via the asymmetric of the Antarctic continents.

④ Southern summer, one-wave in the high latitudes, surface and aloft, showing the orographic forcing of the polar continents. In the low latitudes there is 3-wave pattern surface and aloft, probably a thermal forcing from the three continents in the low latitudes.

* N.H. winter :

sfc : 2 waves ← thermal forcings
upper : 3 waves ← orographic forcings

N.H. summer :

sfc + upper : 3 waves ← orographic

S.H. winter :

sfc + aloft : 1 wave ← thermal + orographic

S.H. summer

high-lat sfc + aloft : 1 wave ← orographic
low-lat sfc + aloft : 3 waves ← thermal forcing

Sol)

N.H. winter :

3 wave pattern aloft, troughs east of mountains ⇒ topographically forced surface ; 2 waves, lows over oceans, highs over land (Asia + North America) ⇒ thermally forced.

N.H. Summer :

3 wave pattern aloft and at sfc ⇒ since east of high topography it suggest orographic forcing mainly.

S.H. Winter :

one wave throughout – thermal/orographic forcing via Antarctic asymmetry.

S.H. Summer :

one wave in high lats due to Antarctic
3 wave in low lats due to thermal (land/ocean) contrasts.

* general atmospheric circulation (4 major factors + characteristics)

MET5135 (Dynamic Climatology): Nicholson (1 hour, 1997, 1998) *

- Describe the 4 most significant factors producing the general atmospheric circulation and describe, for each, the major characteristics it imparts on the general atmospheric circulation.

✓ Describe the main surface and upper air features of the general atmospheric circulation, considering first a simplified zonal view and then adding the most important zonally asymmetric features to the picture.

Sol)

① equator – pole temperature gradient (or differential heating or gradient of insolation) leads to vertical overturning in meridional plane
→ Hadley cell, forced Ferrel cell, weak polar cell.

② Rotation of the earth → Coriolis force
↳ Rossby waves depend on rotation.
↳ rotation imposes limits on type of flows we see in our atmosphere.

③ Distribution of oceans + continents or land/water contrast.
→ leads to zonal asymmetries and interhemispheric differences.
→ E/W temperature gradient, waves in the flow.

④ Large scale topography
→ produces planetary waves, heating aloft, disturbed flow via obstacle friction, blocking of air masses.

* General atmospheric circulation in N.H + S.H

MET?: Nicholson (30 min)

- Question

A. Fully contrast the Northern and Southern hemispheres in terms of the causal factors of climate and general atmospheric circulation.

B. Describe also the major differences in the general atmospheric circulation of the two hemispheres and its seasonal changes. Be sure to consider both thermal and dynamical factors (e.g., orography), and be specific with respect to the wave patterns in winter and summer both at the surface and aloft.

→ see the previous 2 questions.

Sol)

Causal factors :

- land vs weter
- land in low-lats vs mid-lats.
- ocean vs. continent at poles
- Solar distance at solstice (least important)
- major oragraphic effect : low vs midlatitude
  - ↳ SH has little influence of oragraphy on general circulation, also less land ∴ less friction + higher wind speeds in S.H.

Circulation differences

- Zonal in SH, meridional in N.H.
- SH → westerlies stronger, less poleward weakening in summer, less equatorward displacement in winter.
- SH → less seasonal contrast in general
- H + L in broad belt in SH whereas they are individual cells in N.H.

* hydrology eq.

MET? (Hydrology): Nicholson (1 hour, 1997)

- Give an equation for the calculation of evaporation from a water surface, using either the hydrologic balance method or the Penman formula. Explain each of the terms in the equation. Contrast this with the other method, listing the variables used for calculations in each method and describing the physical processes to which each would be most sensitive. What would you consider to be the most important sources of error in the application of these formula to most lakes?

based on In's answer (He got 9/10)

sol)

Hydrologic balance requires : Mass-In = Mass-out

$$\therefore \boxed{E = (P + \text{Inflow} + G_I) - (\text{Outflow} + G_o + \Delta H)}$$

where E : evaporation from surface
P : precipitation to the water surface
Inflow : runoff from catchment to water
Outflow : discharge from the waterbody
G_I : Ground water inflow
G_o : " " outflow
ΔH : water surface change in certain period ✓

If all the terms can be measured, then the amount of evaporation can be estimated.

Consider the energy balance method

For a mean steady state of the water body, which the storage of water body $\Delta S \approx 0$ then the net energy received by the water surface must be balanced by the sensible heat energy to the air plus the amount of energy consumed by the evaporation.

$$R_{net} = S + LE$$

where S : sensible heat transfer
L : vaporization parameter
E : evaporation

Define Bowen ratio $B = \frac{S}{LE}$ $\quad \because R_{net} = BLE + LE$.

$$\Rightarrow \boxed{E = \frac{R_{net}}{(1+B)L}}$$

$$\because R_{net} = R_{sw}^{\downarrow}(1-a_w) - R_{LW}^{\uparrow} + R_{LW}^{\downarrow}$$

where $R_{sw}^{\downarrow}$: the solar radiation received by water surface
a_w : albedo of the water
$R_{LW}^{\uparrow}$: long wave emission from water

Generally, the above terms are determined by

$R_{sw}^{\downarrow}$: Cloudiness
$R_{LW}^{\uparrow}$: cloudiness, surface temperature, emissivity
B : water temperature, air temperature, vapor pressure of air and water.
a_w : season of the year.
L : temperature of water

But B, a_w and L are not sensitive to the changes of parameters they depend on and since we can well measure the temperature, the most sensitive parameter is cloudiness, which is very difficult to estimate and it can cause a big change in the estimation of R_{net} and consequently evaporation even for a small increase/decrease of it.

As for the hydrologic balance method, most of terms needed contain uncertainty like the inflow which also depends on the catchment, evaporation and precip. Out for most closed basin lakes is not a problem. For some cases the ground water terms are hard to measure, since some lakes groundwater contributes a large portion. So this method may be used for small, closed basin and no ground flow waterbody.

- Firstly, cloudiness may be the most important source of error, since it can greatly alter the net radiation received by the water surface and both energy balance and Penman formula primarily depend on the estimate of R_{net}
- Secondly, wind speed which functions in the Penman formula. For some large lakes, the wind speed is hard to estimate: It can affects the evaporation by a great amount.
- Thirdly, water and air temperatures, especially for large lakes, in which temperature may have a different distributions in different parts.
- The other error source may cause from the empirical formula we employ in the calculations, since it depends on the location, time and the researcher.

* water storage

MET? (Climatology): Nicholson (45 min, 1997) *

- Diagram the four water storage locations in an ecosystem and the sources and sinks of water in the system. Describe four ways in which soil water movement is brought about and what factors influence the rate of movement in each case.

? → see the previous question

* Climate types wrt rainfall

MET? (Climatology): Nicholson (45 min, 1993) *

- Describe the major distribution of climate types, worldwide, with respect to the amount (qualitative) and seasonality of rainfall. Describe in detail the causal reasons for this distribution (i.e., particular features of the general atmospheric circulation and how they relate specifically to various geographical regions.

?

* <u>land surface In GCM</u>

MET? (Climatology): Nicholson (45 min)

- How would you represent the land surface in a general circulation model (GCM)? Consider the five major types of surfaces, surface hydrology and subsurface heat and moisture flow. Include, for example, how you would represent rainfall, how many subsurface layers you would want, which processes need by explicitly included, how many categories of soils and vegetation you need and what are the most relevant properties for defining these categories. Be sure to include how you would parameterize evapotranspiration and runoff and produce a simple flow chart to describe the processes in the model. Note: it is important to justify your answers, giving the rationale for the representations you choose.

?

* atmospheric energy cycle

MET?: Nicholson (30 min)

✓ • Describe the atmospheric energy cycle, i.e., the nature of the processes of energy generation, dissipation, and conversion by the general atmospheric circulation. Describe the general energy processes linked with the Hadley and Ferrel cells and with the East-West Walker-type over-turnings.

Sol)

The atmospheric energy cycle evolves in response to latitudinally dependent energy input from the sun, characteristics of the underlying sfc, small scale effects, and transient weather systems.

Because of the strong latitudinal variation of incoming solar radiation, the earth-atmosphere system experiences a net radiative surplus equatorward of about 40°N/S and a radiative deficit poleward of this latitude. Thus a poleward transport of heat is required in order to prevent these regions from cooling or warming indefinitely.

$$\begin{tikzcd}
G \arrow[dr] & & & G \arrow[dl] \\
& A_Z \arrow[r] & A_E \arrow[d] & \\
& K_Z \arrow[u, "?"'] \arrow[dl] & K_E \arrow[l] \arrow[dr] & \\
\varepsilon & & & \varepsilon
\end{tikzcd}$$

A_Z : zonal available potential energy
A_E : eddy APE
K_Z : zonal K.E
K_E : eddy K.E
G : generation
ε : dissipation

In a QG framework, A_Z is generated if the mean diabatic heating is positive where the mean temperature is high and negative where the mean temperature is low. This is actually the case because of the radiative balance of the earth-atmospheric system has a surplus in the warm tropics and a deficit in the cool poles. Potential energy increases in association with the increase pole-to-equator ∇T.

Eventually baroclinically unstable eddies develop and $A_Z \rightarrow A_E$ by the northward transport of warm air and equatorward transport of cold air. At the same time $A_E \rightarrow K_E$ by the vertical motions in the eddies (east-west circulations), specifically the rising of warm air E-NE of L + sinking of cold air W-SW of L. In this way heat is transported both upward + poleward so that energetic equilibrium is realized.

When trough + ridge patterns tilt SW to NE, the eddies transport zonal momentum poleward, on average. The transport helps to maintain the westerlies against frictional loss $\Longrightarrow K_E \longrightarrow K_Z$

The direction of the $K_Z \leftrightarrows A_Z$ transfer is uncertain. If motion is upward where it is cold and downward it is warm (as in a Ferrel cell) we have $A_Z \leftarrow K_Z$.

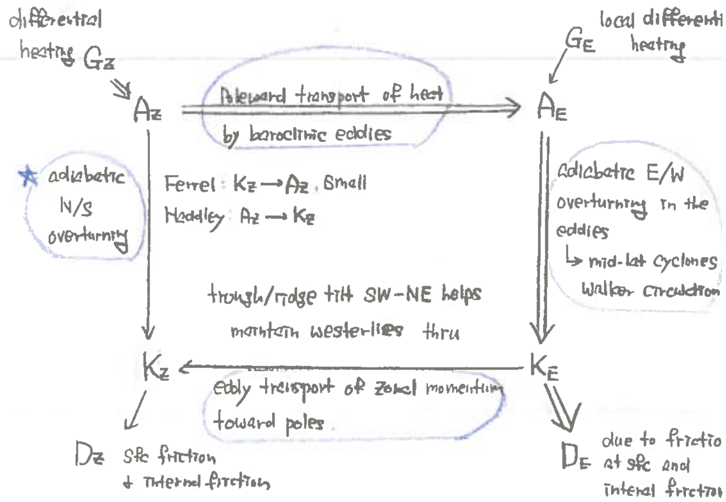
A_Z and A_E are generated by diabatic effects. K_E + K_Z are dissipated by frictional effect.

In the belt within 30° of the equator, the conversion from A_Z to K_Z plays an important role in the maintenance of the Hadley circulation.

In mid latitudes, the transfer of energy flux northward is mainly due to eddies. The zonal mean meridional velocity is much too small to account for a significant fraction of the required circulation.

For the Walker circulation, ∇T along the equator maintains this thermally direct circulation.

Summary



* equatorial westerlies

✓ * Explain at least 3 ways in which the presence of the equatorial westerlies is significant in terms of climate and weather processes.

Sol)

ⓐ Conservation of angular momentum implies that westerlies must increase in speed as we move poleward, decrease in speed as we move equatorward. One approx. form of the vertical motion eq. is

$$\frac{dw}{dt} = \underbrace{-\frac{1}{\rho}\frac{\partial P}{\partial z} - g}_{} + (2\Omega\cos\phi)u$$

↳ $\cos\phi$ max at equator so this term is more important in tropics.

↓ equality between these two terms gives hydrostatic relation

Assume a column of air is in hydrostatic balance with vertical accelerations due to the Coriolis term. If u is positive (westerly) then lifting. If u is negative (easterly) then subsidence.

ⓑ Equatorial westerlies are required for tropical influence on mid-latitudes. Heat source generates equatorial waves if overridden by westerlies. Also necessary for interhemispheric interactions → act as ducts for waves, whereas easterlies block the waves.

ⓒ Westerlies are required for the vertical propagation of equatorial waves.

* Sfc features

* describe major sfc features & how they change from winter to summer.

Sol)

Winter :
1) mid-lat lows dominate → Icelandic, Aleutian ← only "lows" in statistical mean
2) features pushed equatorward
3) Sfc features more intense
4) Polar vortex aloft – more intense, meridional, 3 wave pattern
5) lows over ocean, high's over land.

Summer :
1) Subtropical highs dominate (real long term feature)
2) features pushed poleward
3) Surface features less intense
4) Polar vortex – relaxed, zonal
5) highs over oceans, lows over land.

↖ equatorial trough (ITCZ)
→ equatorial westerlies

* Contrast the troposphere and stratosphere in terms of vertical and latitudinal temperature structure, wind systems and energetics.

Sol)

- vertical
  - troposphere : T decreases with z increasing
  - stratosphere : T increases " " "
- latitudinal
  - trop : –T gradient points from warm low lats to cold high lats.
  - ✓ Strat : cold and warm poles, –T gradient is mainly from winter to summer hemisphere.
- Winds
  - trop : westerly jet in mid-lats, easterly jets in tropics.
  - Strat : westerly jet in winter hemisphere, easterly in summer hemisphere
- Energetics
  - trop : $A_Z \rightarrow A_E \rightarrow K_E \rightarrow K_Z \rightarrow A_Z$
  - * Strat : $K_E \rightarrow A_E$, mainly

$$\begin{tikzcd} K_E \arrow[r] \arrow[dr] & K_Z \arrow[r] & A_Z \\ & A_E \arrow[r] & A_Z \end{tikzcd}$$